DESIGN OF A LOW ENERGY VAN DE GRAAFF GENERATOR AND ACCELERATOR

M. Sc Thesis
in
Engineering Physics
University of Gaziantep

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April 2007

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ABSTRACT

DESIGN OF A LOW ENERGY VAN DE GRAAFF GENERATOR AND ACCELERATOR

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M. Sc in Engineering Physics
Supervisor: Assist. Prof. Dr. Mustafa YILMAZ
April 2007, 57 pages

In this study a low energy electrostatic Van de Graaff generator and a simple linear accelerator tube designs are proposed.

In the present design, a high voltage (HV) spherical terminal is designed from copper, whose electrostatic voltage would be accumulated around 450 kV by a single ply belt driven by a standard 2 Hp monophase electrical motor for the VDG generator part and around 60 % at that voltage would be used for the accelerator system. The proposed design of the simple linear electrostatic high voltage accelerator tube should be attached to the HV generator terminal dome. The sample particle source of the acceleration tube may be replaced by an electron gun or an ion source depending on later decision.

Since the presented VDG generator and accelerator system theoretically designed and some parameters of accelerator system, such as the position of particle source and the dimensions of the accelerator rings and ect., are obtained by a well known particle accelerator simulation program instead of experimental produces, a matrix of experiments should be carried out after the construction of the proposed design, to optimize the reliability of the VDG generator and accelerator system.

Key words: Van de Graaff generator, Simple linear accelerator, Design

ÖZET

DÜŞÜK ENERJİ VAN DE GRAAFF ÜRETECİ VE HIZLANDIRICI DİZAYNI

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Nisan 2007, 57 sayfa

Bu çalışmamızda, düşük enerjili Van de Graaff üreteci ve basit bir lineer hızlandırıcı tübü tasarımı önerildi.

Önerilen tasarımda yüksek enerji sağlayan küre bakırdan tasarlanmış olup yaklaşık 450kV için, 2 Hp güçündeki motorun döndürdüğü tek kayışla sağlandı. Sunulan tasarımda lineer hızlandırıcı için enerjiyi, hızlandırıcı HV terminali, üreteç HV terminali ne yaklaştırmak suretiyle sağlanacaktır. Örnek parcaçıklarımız için elektron tabancası önerilmiş olup, detalarına deneysel sonuçlar ışığında ileride karar verilecektir.

VDG üreteci ve lineer hızlandırıcı teorik olarak tasarlarlanmış olup, hızlandırıcı tasarım parametreleri, parçacık kaynağının pozisyonu, ringlerin iç çapları vb..., tasarım aşamasında bu alanda kullanılan simülasyon programı yardımıyla tesbit edilmiş olup, VDG üreteci ve hızlandırıcısının yapımından sonra deneysel olarak parametreler tek tek kontrol edilerek optimizasyonu sağlamak mümkün olabilecektir.

Anahtar kelimeler: Van de Graaff Üreteci, Doğrusal Hızlandırıcılar, Tasarım

ACKNOWLEDGEMENTS

During the preparation of the thesis, I have received many helps from the staff of the Department of Engineering Physics. Especially I would like to thank my supervisor Assist. Prof. Dr. Mustafa YILMAZ for all this help and advice during the preparation of this thesis.

And thanks to my grandfather.

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LIST OF SYMBOLS

A : Cross section area of support rods

A_b : Belt area

C : Capacitance

E : Uniform electric field

E_{ym} : Young Modules of the material

e : Charge of electron

g : Gravitational mass

I : Short circuit current of HV terminals

$I_{inertia}$: Moment of inertia

i : Current flowing from the sphere during discharge

i_u : Current from the belt during the change loading, down current

i_b : Current transferred by the belt, up current

l : The length of the accelerating tube

L : Length of support rods

L_e : Effective length

m : Mass of VDG dome and upper roller support

M : Motor revolution for second

m_{par} : Mass of accelerated particle

Q : The charge on the spheres

q : Charge of accelerated particle

P : Applied force

$P_{buckling}$: Buckling force

R : Resistance of HV Terminals

r : Radius of sphere

r_d : Roller diameter

σ : Surface charge density of belt

σ_y : Yield strength

ϵ_0 : Permittivity of free space

ϵ_r : Relativite primitivity

U : Electrostatic energy

υ : Velocity of the belt

V : Potential accumulated on dome

w : Belt width

CHAPTER 1

INTRODUCTION

In 1929 Robert J. Van de Graff invented an electrostatic generator now called a Van de Graff (VDG) Generator. This device is one of the simplest and one of the most effective electrostatic accelerators. It uses a moving belt to carry charge to the inside of a hollow conductor supported on an insulating stand. In such a system, the conducting sphere will accept excess charge and distribute it uniformly on the surface of the sphere despite the repulsive nature of the static voltage. The electrostatic discharge can occur readily at sharp points on the sphere. Van de Graff generators have four major components and can often generate potential differences of up to 30 MV.

1.1 Development of the Van de Graaff Generators

The movement of electromagnetic charges was recognized as a possible process for creating very high voltage. Systems that move charged particles were proposed by nuclear physicists as possibly being liquid, and not necessarily solid, such as a belt. Corona spray had been recognized as a charge that could be applied to a belt; but the question was how to collect the charge from a moving belt. Van de Graaff, being a physicist, recognized that if you ran a belt between pulleys, one pulley at ground and one at isolated environment, supported by insulators, voltage could be generated, but the difficulty was to move charges off of the belt that is carrying the charge. For instance, if charging with positive charges, when trying to bring more charges up, the sphere is trying to push them away. What Van de Graaff discovered was the concept of using a re-entrance structure, where the belt enters inside the sphere. That is the very key component, because once inside the sphere, the charges are naturally drawn to the sphere, trying to get to the outside surface of the sphere. There's a force to move charges from anywhere inside the sphere to the external surface of the sphere. By bringing the pulley inside the sphere, which is the charge-collector, it was very efficient and effective to remove the charges off the belt [1, 2].

In 1929 a small model was constructed and used to demonstrate the soundness of the principles involved. This model was quickly modified but performed as expected. The highest voltage obtained was about 80,000 volts, being limited by the electrical breakdown of the surrounding air.

In that time a larger generator contained in a dismountable tank which could be highly evacuated by a suitably designed combination of high-speed mercury condensation pump and liquid air trap was constructed. During the following years (around 1931) considerable work has done to get a Van de Graaff generator in a perfect vacuum. This generator was designed and developed about 1,500,000 volts and delivered a current of about 25 microampers. It was constructed with 24-inch spherical electrodes mounted on 7-foot upright rods and charged by 2.2-inch silk ribbon belts moving with a linear speed of 3500-foot per minute, and it operated either by self-excitation or by the spraying on of charge from a small 10,000-volt transformer set. It is interesting to note that although it was constructed at a total cost for materials of only about $100. This generator was described at the Schenectady meeting of the American Physical Society in September, 1931 [2].

R. J. Van De Graaf designed respectively for 80,000, 1,500,000 and 10,000,000 volts, and the fourth being an essentially similar generator operating in a highly evacuated tank. Methods are described for depositing electric charge on the belts either by external or by self-excitation [3]. The upper limit to the attainable voltage is set by the breakdown strength of the insulating medium surrounding the sphere, and by its size. The upper limit to the current is set by the rate at which belt area enters the sphere, carrying a surface density of charge whose upper limit is that which causes a breakdown field in the surrounding medium, e.g., 30,000 volts per cm if the medium is air at atmospheric pressure. The voltage and the current each vary as the breakdown strength of the surrounding medium and the power output as its square. Also the voltages, current and power vary respectively as the 1st, 2nd and 3rd powers of the linear dimensions [3].

Van Atta and Van de Graaff made a desirable a new type of vacuum tube for High Voltage Generator around 1932 [4]. A description has given of tests with a high-voltage tube of simple and rugged design. The tube consists essentially of a fiber cylinder extending between the electrodes and evacuated to a pressure of 4×10^{-6} mm Hg during operation. A potential of 300,000 volts could be maintained on a section of tube 53 cm long. In spite of the fact that the voltage was limited by discharge there was no case of puncture. A simple clear-cut mechanism for the initiation of discharge in vacuum (independent of field currents) is given together with confirming experimental evidence.

In1933 had appeared a general discussion of the principles involved in the electrostatic production of high voltage by means of belt generators operating at atmospheric pressure. There was included a brief description of the external structure of the Round Hill electrostatic generator. During the intervening period a belt-charging system has been designed, constructed, and improved by Van Atta and his collaborators [5, 6], so that a very steady, controllable voltage have supplied for nuclear research. Complete generator performance data have been obtained through the utilization of the generating voltmeter which, with proper precautions, has proved to be a convenient and reliable instrument for voltage measurement.

The design technique of operation and performance of the Round Hill electrostatic generator are presented in some detail at Physical Review Vol.49 (1936). The problems of operating wide paper belts, of eliminating vibration, and of controlling humidity are discussed [5]. The original belt charging system, with the belts operated at saturation charge density, is described and its range of usefulness has indicated. A consideration of the problems of voltage control and voltage steadiness at reduced charging currents leads to two modified designs of the belt charging system. The maximum charging current was 2.1 mA and practically independent of voltage. The highest voltage obtained consistently without sparking around 2.4 MV between the terminals. At this voltage there was 1.1 mA of current available for application to an accelerating tube.

The Carnegie Institution group built first a 1-m-diam generator which supplied 600-kV ions by 1933. Then they developed a concentric-shell generator with a 1-m inner shell and a 2-m outer shell, mounted on a tripod arrangement of three textolite columns. Two charging belts crossed the room horizontally, and a vertical discharge tube led through the floor, so that the beam of ions could be analyzed magnetically and experiments performed in a basement room. Potentials of up to 1.3 MV could be maintained with the terminal positive (for accelerating positive ions to ground). Tuve, Hafstad, and Dahl [6] were put to immediate use in accelerating protons and deuterons for nuclear experiments. These were the first practical electrostatic accelerators, and an important series of research papers followed the completion of the 2-m generator in 1935, starting with measurements of excitation functions which showed sharp nuclear resonances [7].

One of the most important technical developments of the Carnegie Institution group was the study of voltage calibration for such air-insulated generators. It was found that sphere-gap calibrations could not be extended to this voltage range with any confidence, but were a function of the meteorological and surface conditions of the gap electrodes. A high-energy proton beam could be brought through a thin vacuum window and the range measured, but the inherent errors in range straggling and the imperfectly known range-energy relations made this calibration also suspect. The first satisfactory calibration was obtained by deflecting the emergent beam of protons by a magnetic field through a system of slits.

The most accurate calibrations were based on the use of a column of precision resistors paralleling the discharge tube[8]. Accurate current measurements with this 10,000-megohm resistor column gave an absolute calibration which was of tremendous value to the scientific world at that time. Nuclear resonances, such as the $C(p, \gamma)$ resonances at 400 and 480 kV, the $Li(p, \gamma)$ at 440 kV, and the three $Y(p, \gamma)$ levels at 328, 892, and 942 kV [7, 8] were observed and measured using extremely thin targets. These and other nuclear resonances have since been determined with such precision that they are used as substandard for calibrating instruments in other laboratories and in providing a cross-calibration of results from different laboratories.

Meanwhile a parallel development started in laboratories, based on the use of high gas pressure to insulate the terminal and increase the potential. Barton, Mueller, and L. C. Van Atta [9] at Princeton were the first to experiment with this modification. They used a cylindrical electrode supported by two textolite , a non-flexible polymer composite, cylinders along the axis of a horizontal pressure tank. Their first small machine developed 1-MV potential at 7 atm air pressure, showing an almost linear increase in breakdown potential with increasing pressure. The chief advantages were the smaller size of the installation and the positive control of humidity within the pressure tank. The first model reached 0.75 MV. The second, described in 1937 and again after further development and operational experience in 1938, it has operated at 2.4 MV. The third model, reported by Herb, Turner, Hudson, and Warren [10] in 1940, introduced the use of three concentric high-potential electrodes to distribute the potential drop and reached a potential of 4.0 MV.

Large pressurized generators were built at the Westinghouse Research Laboratory [11] at the Carnegie Institution, and at the University of Minnesota. They have designed it to operate at relatively low (60 to 120 psi) gas pressure, in the hope that higher voltages could be most readily obtained by increasing the gap and the radius of curvature of the terminal. Recognition of the adverse effect of large terminal area, of the importance of polished surfaces, and of the value of multiple-shell terminals came later. As a consequence, all have been restricted to less than their theoretical limits, operating at about 3 MV.

Trump and Van de Graaff [12] discusses on the first of a series of generators for electrons intended for use as a source of X-rays for medical and industrial purposes. Their studies have included such problems as the flashover potentials for solid dielectrics in vacuum and in compressed gases, the influence of electrode material on breakdown potential, the relative dielectric strengths of various gases such as Freon, CCI_4, and SF_5, and ionization as a function of depth in tissue like material for high-voltage X-rays and electrons. The use of compressed gases as insulating media was investigated experimentally at an early date, and test equipment was set to study the problems and determine the limitations.

Results of the years of comprehensive study on electrostatic problems at MIT are incorporated in the design, and the wide experience of the staff has gone into many later constructions [13].

J. Van de Graaff died on 1967 in Boston at the age of 65. At the time of his death, there were over 500 Van de Graaff particle accelerators in use in more than 30 countries. Now most of the Physics department of universities, even high schools in western countries, especially in USA, have at least one VDG generator and accelerator for educational and experimental purposes. Also many important Nuclear and Particle Research centers have them to inject particles to high energy accelerators [1, 14].

1.2 Application of the Van de Graaff Machines

The VDG (Van de Graaff) generators and accelerators have proven to be a very powerful tool in modern physics. Nuclear structure and nuclear interactions could be studied with the low-energy beams of particles and ions produced by VDG accelerators. They have been played an essential role in ion beam analysis and high-energy implantations. Although they are, getting used more widely in many novel industrial and medical applications, such as brain tumor treatments in medicine [15, 16], and new structure researches of polymers [17] and are widely used both by itself and as an injector or starter for very high-energy machines.

The main advantages of VDG machines are:

- Any charged particles can be accelerated,
- The energy dispersion is quite low,
- The terminal voltage and thus the energy of the particles can be varied quite easily,
- The intensity of the beam is continuous.

The main disadvantage of these machines is only the limitation of terminal voltage due to voltage breakdowns.

Recently, there was a very large machine produced in Europe, designed for over 20 million volts, to meet the needs of researchers interested in using X-rays to alter materials; radiation can be a very effective cross-linking agent to improve the properties of materials. An example of work MIT has done in cooperation with Massachusetts General Hospital involved the use of radiation to improve the material used in hip replacements. Before that development the material used for hip replacement would last 10–15 years, and then the patient would expect to undergo an operation for a new replacement. With the present use of radiated material technology, hip replacements appear to be permanent, not wearing out in one's lifetime [1].

There are many other applications where radiation is a very effective application. Plastics of many kinds are cross linked to make them stronger, more durable, and operate at higher temperature, and organic materials can be made electrical conductors. Semiconductor devices can be irradiated to improve their operation [18].

In summary, the application fields are as follows ;

1- Polymer structure researches by ion irradiation [17],

2- Medicine (Boron-Neutron Capture Therapy) for some brain tumors [15, 16],

3- Ion beam analysis [19],

4- High-energy implantation [18, 19] and

5- Determination/estimation of the age of the materials or the ancient ruins (^{14}C dating, based on the counting the number of ^{14}C -atoms relative to ^{12}C).

A- Polymer structure investigations with ions and neutron beams

Low energy neutron irradiation technique allows one to get information on small changes in polymer structure like and other possible structures such as Poly L-lysine (PLL), and poly ethylene glycol (PEG), co-polymer Poly L-lysine-graft-poly ethylene glycol (PLL-g-PEG) [17].

A first model of such studies and measurements suggests that some parameters, such as persistence length and local conformation of poly PEG chains, could be retrieved from such measurements, may result good results in the production of textile fibers, plastics and other products based on polymers.

B- Medical Brain tumor therapy

Boron Neutron Capture Therapy in which Boron is used for tumor therapy (especially brain tumors) [5]. This method carried out in two steps. First, ^{10}B (isotopes) nuclei are collected in tumor cells by given diluted radionuclide solutions and then in the second stage, some amount of low-energy neutrons are directed on the target tumor. In the ^{10}B neutron absorption reaction it breaks into pieces having two charged particles nuclei (^{7}Li and ^{4}He) which are damages only the tumor's cells on which the ^{10}B nuclei are delivered and collected previously.

C-Nuclear experiments often require low energy

Nuclear experiments often require low energy (less than 10 MeV) ions. Astrophysics experiments that investigate stellar nuclear reactions require low energy collisions. The low energy beams for these investigations can be efficiently supplied by Van de Graaff accelerators. Van de Graaff accelerators can produce nearly mono energetic (all particles having the same energy) beams.

D-The Bremsstrahlung x-rays production

The Bremsstrahlung x-rays produced by the electrons striking a target could also be used for some other experiments. By using a positive ion source, experiments could be performed with beams of ions, and positive ion beams can be used to create neutron beams for neutron scattering and absorption experiments with some instruments.

In the next chapter, chapter 2, a theoretical background on the VDG generator and simple linear electrostatic accelerator have been presented.

In the third chapter, a simple low energy VDG generator and simple low energy HV accelerator design is given with all the details. All the parts are designed by using a well know engineering and simulation software, as used in particles accelerator designs. Detailed technical drawings are all presented together.

Finally, the construction of the designed generator and accelerator system and some experiments have been suggested to optimize the whole system efficiency as a further study in the conclusion section.

CHAPTER 2

PHYSICAL PRINCIPLES OF VAN DE GRAAFF GENERATOR AND ACCELERATOR

The belt-charged electrostatic generator has been so successful as a voltage source for particle acceleration that it has replaced all other static machines and most of the other types of direct-voltage generators. The use of high-pressure gas insulation has freed the generator from atmospheric disturbances, and has resulted in a relatively compact design. In the energy range up to 6 or even 10 MeV to which it has been developed, it can deliver a steady, parallel beam of particles free from stray radiation which makes it ideal as a source for nuclear studies in this energy range and in medical applications to produce high energetic x-rays.

2.1 Principle of VDG Generator

The electrostatic machine is simple in concept, but the techniques and designs needed to obtain engineering perfection are complicated with details and are bounded by fundamental limitations, such as the electrical breakdown of insulation. All these limitations and design parameters will be discussed in ongoing sections and in the next chapter

2.1.1 High Voltage Terminals

A simple a diagram of the complete intended VDG design is given in Figure 2.1. The structure consists of a rounded high-voltage terminal supported on an insulating column and a moving belt to carry charge to the terminal. Charge of one polarity is sprayed on the belt at the grounded end is carried up into the terminal by a moving belt, and is removed by a collecting device within the

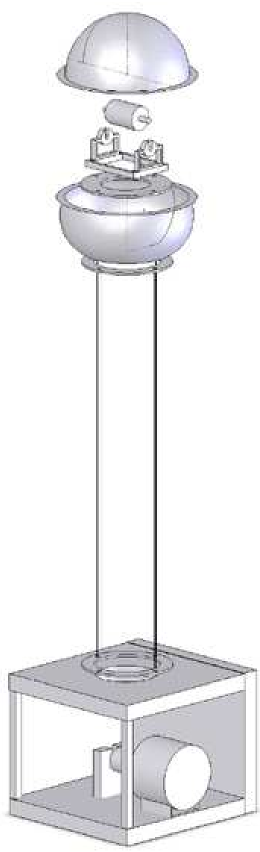

Figure 2.1: General 3D view of the designed VDG Generator.

terminal where there are no high electric fields to disturb the collecting process. This steady current,

$$i = \frac{dQ}{dt} \tag{2.1}$$

produces an electrostatic potential on the terminal. If C is the capacitance of the terminal to ground, the terminal will be raised to a potential V by a charge,

$$Q = CV \tag{2.2}$$

The rate of increase of potential with time is given by

$$\frac{dV}{dt} = \frac{i}{C} \tag{2.3}$$

$$i = C\frac{dV}{dt} \tag{2.4}$$

where i is the current flowing to the capacitor. The Current i consist of the up current (charge brought to the high voltage terminal by the belt) and the down current (charge that bleeds off the high voltage terminal).

For the intended design of the Van de Graaff generator, the up current is constant, while the current down flowing through the equipotential rings of the accelerator tube and support column is proportional to V. Therefore

$$i = i_u - \frac{V}{R} = C\frac{dV}{dt} \tag{2.5}$$

where $i_u$is the current from the belt, R is the resistance of high voltage terminal, and

$$\frac{V}{R} \tag{2.6}$$

is the current that is lost to the corona effect and down the equipotential rings and support column. When the Van de Graaff generator is first turned on ($t = 0$), the potential is zero and

$$\frac{dV}{dt} \tag{2.7}$$

(the rate the potential of the sphere is charging)is large. After a period of time,

$$\frac{V}{R} \approx i_u \tag{2.8}$$

and

$$\frac{dV}{dt} = 0 \tag{2.9}$$

which means that the voltage remains constant. Reorganizing Eq.2.5 we get the differential equation

$$\frac{dV}{dt} + \frac{V}{RC} = \frac{dV}{dt} \tag{2.10}$$

Eq.2.11 provides the time dependent voltage equation for a Van De Graff generator :

$$V = i_u \times R(1 - e^{-\frac{t}{RC}}) \tag{2.11}$$

Now, since the breakdown field of air is approximately 30 000 V/cm. we find that the maximum attainable voltage on a spherical high voltage terminal is given by

$$E_{sphere} = k\frac{Q}{r^2} = \frac{V}{r} \tag{2.12}$$

where E_{sphere} is the electric field of sphere, Q is the charge on the sphere, r is distance from the center of sphere to a point outside of the sphere (in this case r is the radius of the sphere because we want to find the voltage on the surface of sphere), and V is the voltage of sphere, $k = \frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 (Nm^2/C^2)$. Therefore, given the maximum electric field of a sphere surrounded by air [21],

$$V = E_{sphere} \times r = 30\ 000\frac{V}{cm} \times r \tag{2.13}$$

2.1.2 Charge Conveying System

The belt runs between a motor-driven pulley at ground potential and a pulley in the terminal. Electric charge is sprayed on the belt at the grounded end from a fine wire or from a row of corona points extended across the width of the belt and directed at the pulley or at a grounded plate behind the belt. A corona discharge maintained between these points and ground produces gaseous ionization in the air, and charge is deposited on the moving belt. If the terminal is to be charged positively, the points must have a positive potential relative to ground, so that positive ions will go toward the grounded pulley or plate and will be intercepted by the belt. If the terminal is to have a negative charge (for accelerating electrons), the corona points are made negative.

The charge is removed from the ascending belt within the terminal by a similar corona-point collector connected electrically to the terminal. If the pulley within the terminal is insulated, it will rise to a potential sufficiently above that of the terminal to maintain the necessary corona discharge. The charge appears on the outer surface of the terminal, so that (except for the effect due to the pulley potential) the inside of the terminal is field-free. Thus the charging process occurs within the grounded base, and the discharging of the belt takes place within the equipotential terminal; both operations are separately controllable and independent of terminal voltage.

The electric-power supply used to produce the corona discharge from the needle points. Potentials of 20 to 30 kV are sufficient, and a current capacity of several milliamperes is required. A half-wave, hard-vacuum-tube rectifier is common, using 60-cycle power. Filtering to reduce the ac ripple is useful in giving more uniform belt charge, but not essential. The magnitude of the corona spray current is usually controlled by varying the primary ac voltage. This corona current determines the potential to which the terminal will rise, as will be described later.

It is also possible to spray charge of the opposite sign 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 ascending and descending, and the charging current is doubled. The resistor placed between the insulated upper pulley and the terminal can be adjusted to control the upper spray potential and arranged to make the charge densities equal on the upward and downward runs.

The power required to charge the terminal is calculable from charging current and terminal potential. In a positive-ion accelerator the useful current is the beam of positive ions being accelerated down the accelerator tube. However, stray ions may strike the tube walls and may release secondary electrons, which are accelerated up the column to produce X-rays on striking the ion source. Frequently a resistive load is built into the insulator column to serve as a potential divider. This may be of the order of 1000 to 10,000 megohms, uniformly distributed along the length of the accelerator tube and connected to appropriate electrodes along the column. The ultimate limit to terminal potential in the absence of an accelerator tube is corona discharge from the terminal. This is caused by the breakdown of insulation (either gas or solid) due to excessive fields at the surface of the terminal. In most installations adjustable corona-point units are installed opposite one point on the terminal surface to increase or decrease total load current and so to maintain a constant terminal potential. Occasionally a corona streamer in the gas will develop into a spark which discharges the terminal completely.

The required charging current is the sum of these several components, which behave differently with terminal voltage:

1. Positive-ion current is generally constant, determined by ion-source conditions rather than by total voltage.

2. Current in the resistive potential divider or leakage down the column is directly proportional to terminal potential.

3. Secondary electron current in the tube will be described in more detail in a later section, where it is shown to increase rapidly with voltage above an apparent threshold.

4. Corona current behaves similarly, being zero at low voltages and rising rapidly above a threshold value.

After a spark has discharged the terminal and while the total load current is small, the excess charging current causes terminal voltage to rise rapidly. However, as terminal voltage approaches its equilibrium value again, the excess current becomes smaller and the rate of charging decreases. In principle the terminal voltage will approach the equilibrium value asymptotically, but in practice the corona-control system for voltage stabilization allows an overshoot. The time constant of this control system varies inversely with the magnitude of the corona-current variation used in the control.

The operation of the generator is simple to describe. First the belt motors are started; then the belt-spray charging unit is turned on and the rate adjusted to bring the terminal up to the working voltage, balancing the currents on the ascending and descending belt runs.

Charge-Carrying Belt

The basic idea of a belt type generator probably goes as far back as Lord Kelvin who suggested at the end of the 19^{th} century an electrostatic generator in which charge would be carried to the high-voltage terminal either by a belt or by a belt conveyor consisting of alternate insulating and metal segments [22].

An endless insulating belt runs between two pulleys at a constant linear speed of several to tens of m/s as shown on Figure 1.1. A metallic charging point or screen at a voltage of several kV acts as emitter. A corona discharge sets in and the gas surrounding the points is ionized. According to the polarity of the screen, positive or negative charges are deposited on the belt and carried up to the terminal electrode. The current i_b transported by the belt is giving by [21],

$$i_b = \sigma w v \tag{2.14}$$

The current delivered by a belt of width w (cm), speed v (cm/s), σ is the surface charge density on the belt.

The characteristics of the ideal belt should have [23]:

- high resistivity $10^{13} - 10^{14}$ Ω,
- little stretch,
- moisture resistant,
- sufficiently smooth surface,
- high mechanical strength,
- low cost.

Flat, endless belts of insulating material have thus far proved to be the most effective charge conveyors for both air-insulated and compressed-gas electrostatic generators. The belt must have high mechanical strength, high surface and volume resistivity, and high dielectric strength, and it should be fire-resistant if air is to be used as the insulating medium. Another important requirement is that the belt should not absorb moisture when the housing is opened to the atmosphere for maintenance or repair, or else that the time required for dehumidifying the belt be short. Belt speeds are commonly between 914 and 1524 m/min.

Most VDG where belts are driven by motors installed within a base pedestal at ground potential as will be explained in next chapter for the charging accumulation or electron loading.

Maximum Stored Energy and Capacitance

Belt charge density is limited by breakdown, and the same limiting field applies as for terminal potential. If the electric field due to belt charge is uniform and directed normal to the belt surface in both directions, the maximum charge density $\sigma_{\max}$ is given by [21],

$$\sigma_{\max} = 2\epsilon_0 E_{\max} \tag{2.15}$$

where $E_{\max}$ is the maximum uniform electric field, $\epsilon_0$is the free space permittivity, which is 0,085 pF/cm for air.

The transferred charge could be written using κ, the dielectric constant (roughly unity for air), and A, the area, the current obtained as

$$i_b = \frac{\kappa}{4\pi k}\frac{V}{r}\frac{dA}{dt}$$

Using the fact that the maximum potential per centimeter is 30,000 kV, M as the motor revolution per second, r_d as the roller radius, ω as the width of the belt, A_b as the total belt area and the belt area which carries the charge per second$\left(\frac{2\pi r_d \times M \times \omega}{A_b}\right)$, then the belt current could be found as $4.5\mu A$.

For small low energy type generators operating in room air, however, the E field limit is usually applicable as,

$$E = \frac{V}{r} \tag{2.16}$$

where E is the field at surface of a sphere, V is the accumulated voltage, r is the radius of sphere.

The total capacitance of the sphere is, as know,

$$C_{sphere} = 4\pi\varepsilon_0\ r \tag{2.17}$$

The stored energy which will be seen when we discharge it, as know electrostatic energy (U), depending on capacitance (C) and the voltage (V) is

$$U = \frac{1}{2} \times C \times V^2 \tag{2.18}$$

2.2 Principle of VDG Accelerater

In electrostatic high voltage accelerators, the beam travels between the high voltage terminal and ground potential through a highly evacuated accelerator tube. Metal electrodes are sealed to dense, low outgassing insulating rings. Different types of bonding could be successfully used [23]:

- glass sealed with polyvinylacetate to aluminum, titanium or stainless steel electrodes

- high density alumina ceramic sealed with aluminum metal to titanium electrodes

Bonding is of course an important issue with respect to the mechanical strength of the tube and its tightness to vacuum. The tightness of the bonding archered by using rods through specifically designed and drilled holes, as did in this design study.

Spark gaps protect the fragile insulators against sparks. The voltage between the electrodes is established by resistors or corona points draining current from the high voltage terminal.

The performance of accelerator tube in an electrostatic machine depends, among other things, on the vacuum conditions in the tubes. In the absence of vacuum pumps, the vacuum depends on the gas load and the conductance of the tubes. The metal electrode is of course fitted with a central aperture for the passage of the beam. This aperture follows the envelop of the beam along the tubes. It is essential to provide additional apertures for adequate pumping. The relative position of these apertures are shifted from one electrode to the other so as to prevent the acceleration of secondary electrons.

The ideal insulator has the following properties [23] of the accelerator rings:

- high volume breakdown strength,
- low dielectric constant,
- secondary emission coefficient should be less than 1,
- no voids in the adhesive film layer,

- no sharp edges in the bonding foil or no stress raisers in the adhesive fillet,
- insulator profile shaped to minimize the fields due to polarization and surface charge if present.

2.2.1 The Accelerating Tube

Uniform drop in potential results in a constant electric field (E) field of magnitude $\frac{V}{L}$, where L is the length of the accelerating tube. A constant voltage drop produces and electric field with the field lines running parallel to the axis of the accelerating tube. Combining the Lorentz force with Newton's second law yields an electron acceleration of magnitude

$$F = qE = m_para \tag{2.19}$$

then,

$$a = \frac{qV}{Lm_par} \tag{2.20}$$

where q is the charge of the particle and is m_{par} the mass of the particle which is valid for each ring or group of rings.

The length of nth tube could be calculated by,

$$l_n = \sqrt{\frac{nqV}{2m_par}} \tag{2.21}$$

which is usually used for RF accelerator system. For the relativistic particles the tube lengths are roughly constant.

CHAPTER 3

DESIGN OF VAN DE GRAAFF GENERATOR AND ACCELERATOR

In this chapter, the design of a simple, low cost, air insulated, direct current high voltage electrostatic generator and an accelerator, suitable for simple research and education applications for small Labs will be explained as the theory of had been discussed in previous chapter.

The intended generator design capable of accumulating 450 kV and should produce a short-circuit current of about 4,5 microamper, due to some effects 60% of the theoretically calculated voltage could be actually accumulated using a 8 cm×279 cm 2 hp-motor driven belt. Also, a small particle accelerator system, attached to the generator, have been designed. Some parameters, such as the ring parameters, of the accelerator tube have been found by using a well by known accelerator simulation software SIMION 3D [24].

All the technical drawings modeled in detail for each part by using SOLID WORKS 2005 [25].

3.1 Design of High Voltage Terminals

The maximum voltage developed on the terminal depends only on the shape of the terminal, its insulating support from ground, and the insulating media surrounding it. For air-insulated generators the shape must be such that the desired voltage the gradient at all point on the electrode surface is well below the ionizing value of approximately 30 kV per centimeter [3, 13], for a terminal isolated in space is a simple sphere.

In the present generator, 1 m support column is designed to increase the voltage insulating strength and it also increased by adding between re-entrant electrodes 15 cm transverse rings by applying along the outside of the column, as shown Figure 2.1. On increasing the insulating length of the column to 1.30

Figure 3.1: Copper hemi-sphere. Dimensions are shown on technical drawings and given in appendix B with Part number 1.

m, however, the addition of these rings maybe advantageous, also, by increasing the length of the belt.

Designed Van de Graaff generator has an upper electrode about 30cm in diameter which actually has a minimum radius of 15cm using the Eq:2.13 one can easily calculates the maximum accumulated potential as 450 kV, so that our maximum voltage will be around 450 kV with two copper hemispherical high voltage terminals.

3.1.1 Design Parameters of the Terminals

The high voltage terminal is taken as two 30 cm diameter and 15 cm in depth hemi-sphere joined together at the equator by overlapping structure for simplicity. Also a tape additionally could be in order prevent slipping the hemi-spheres in the construction.

The sphere used on the top on the VDG can be constructed from two copper hemi-spherical bowls. In this study copper had been choosen because of the cost of the system. The bowls are designed as 30 cm dia x 15 cm deep from the outer most rim as shown Figures 3.1 and 3.2 The bowls need to be fixed together with overlaps of 1 mm$\times$1 cm. All hemi-spheres must have smooth surface so should be polished.

The mass of the 2 mm-thick copper spherical dome would be 5 kg and then the total mass of the high voltage terminal, including the rollers, bearings, roller support system and the frames, would be 7 kg.

3.1.2 A Hole for Insulating - Support Column

One need to cut a hole in the bottom of one of the copper bowls which will be used as the lower hemi-sphere. A hole would be cut 7.5 cm radius at the

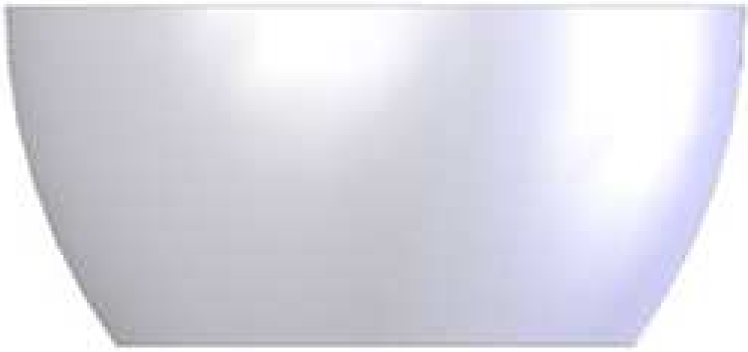

Figure 3.2: Lower Copper Hemi-Sphere. Dimensions are shown on technical drawings and given in appendix B with Part number 2.

bottom and a 3 cm around the cut should be flattened to connect the support column flange which the roller will be assembled on it, as shown Figure 3.3.

3.2 Charge Conveying System

As previously explained electrostatic belt generator consists essentially of a well-rounded high voltage electrode supported from ground on an insulating column and of a charge-conveying system of rapidly moving insulating belts running between this terminal and ground. The following description of the charging arrangement makes use of the diagram shown in Figure 1.1

The generator described employs a singe-ply rubber-fabric belt about 0,3 cm. thick, 8 cm wide, and 279 cm long in endless length. The belt is driven at approximately 684 meter per minute by the induction (monophase) motor, on which the belt-coupled to the lower pulley or namely "lower roller".

The maximum current capacity of a belt generator depends simply on the width and speed of belt, the number of belts, and the insulating medium in which the belt runs. The theoretical maximum charge density which can be placed on the belt is that which will give a gradient of about 30 kV per centimeter, and hence is equal to 4.4×10^{-9} coulomb per square centimeter, assuming the maximum gradient exists on both sides of each run of the belt. In practice the short-circuit current capacity is usually about 60 percent of this theoretical value.

All hemi-spheres must have polished surface, because every cm must keep 30 kV [3, 13].

3.2.1 Electron Loading Mechanism

At the lower grounded end the electric charge is sprayed on the belts from corona points directed at the pulley and separated from it about 1 cm. These

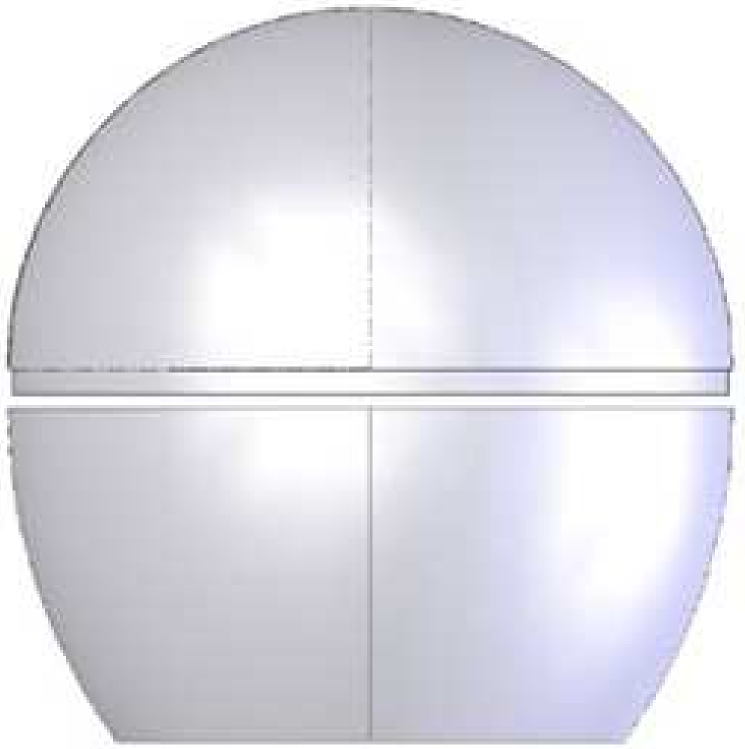

Figure 3.3: VDG bowls which will be fixed together with overlaps.

corona points are maintained by a small transformer-rectifier set at a potential which can be varied up to about 10 kV for an efficient and powerful VDG system. The resultant ionization of the air in the vicinity of the points causes a transfer toward the pulley of electric charge which is intercepted by the intervening insulating belt. This charge neutralizes the charge of opposite sign may be on the belt from its downward run and leaves a net charge to be carried to the upper terminal. The amount of charge sprayed on the belt in this manner is controlled by regulating the voltage of the power supply which will be determined by experiments and have been omitted in this study since it is out of scope.

It is evident that within the high voltage terminal a similar arrangement, involving a second transformer-rectifier, may be employed to neutralize the charge brought up and to charge the descending run of belt with opposite polarity. While this is advantageous in large units for low energy generator a simple self-inducing arrangement have been used to perform this function. This consists in insulating the upper pulley and causing it to be charged to a potential higher than that of the terminal by means of a collector connected to the pulley and placed just below the point of tangency of the arriving bell. This self-excitation method has been described in detail in references [3, 13].

3.2.2 The Support and Insulating Column

The support column will be composed 4 Hight Density polyethylene (HDPE) rods having a yield strength of 26-33 MPa [26]. For the radius of the rods one could check the loads on the rods by using static equilibrium condition [27], that is,

$$\sigma_y = \frac{P}{A} \tag{3.1}$$

or

$$r_r = \sqrt{\frac{mg}{4\pi\sigma_y}} \tag{3.2}$$

where σ_y is the yield strength, r_r is the radius of the rod, P is the load and g is the gravitational constant. Then 1 cm of the diameter of the rods which is commercially available will be excellent for the support structure. The rods should be fixed with connecting rings as shown in Figure 3.4 having 22 cm outer, 15 cm inner diameter, 0.5 cm. thickness. The rings will be used to fix the column to the below hemispherical high voltage terminal by suitable screws through Hight Density polyethylene (HDPE) as shown Figure 3.5.

The outside diameter of insulating column would 8 cm and the length have been taken as 100 cm since HDPE are available as 1 m long and 1 cm in

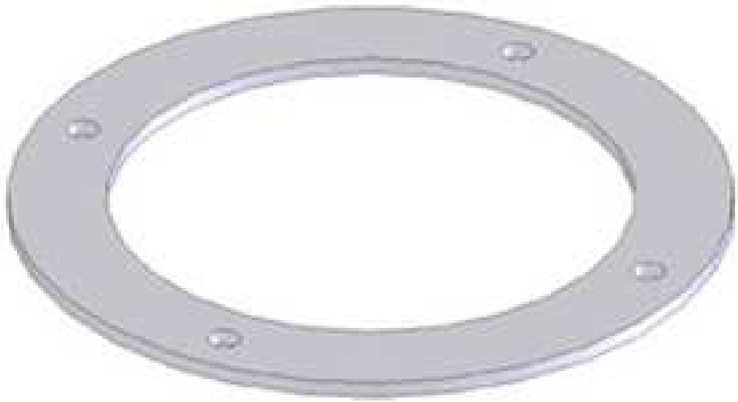

Figure 3.4: Two connection HDPE rings for fixing the support column and the lower high voltage terminal. Dimensions are shown on technical drawings and given in appendix B with Part number 3

diameter. 1 m net length of support column would be enough for preventing discharge and would be sufficient for the required belt length. The outer surface of HDPE structure of the support column will be covered by an insulating plastic material.

The whole structure, again, ensured for the buckling by using [27]

$$P_{buckling} = \frac{\pi^2 \times E_{ym} \times I_{inertia}}{L_e^2} \tag{3.3}$$

where E_{ym} is the Young Modules of the material, $I_{inertia}$ is the moment of inertia and L_e is the effective length. If both end fixed, as in our case, $L_e = 0.7L$ and $I_{inertia}$ and is 0.01^4 if the possible buckling would be turning around itself and will be divided to the number of rods.

$$P_{buckling} = \frac{\pi^2 \times 0.8 \times (\frac{\pi \times 0.01^4}{4})}{0.7(1)} \tag{3.4}$$

As seen, $P_{buckling}$ is 3.5, which is much less then the total load, P, of the dome.

3.2.3 Roller

Two Rollers can be made from HDPE for insulation and to support Figure 3.6 the rolling mechanism of the belt connected to support system by bearings at both ends of the central rod. The roller surface, where it is contact with the belt, should be made rough to increase the friction and to prevent the slippage.

3.2.4 Rollers and Support Mechanism

Upper and lower roller and supporting system constructed from HDPE. The roller is a cylindrical system and the base material is HDPE support. The

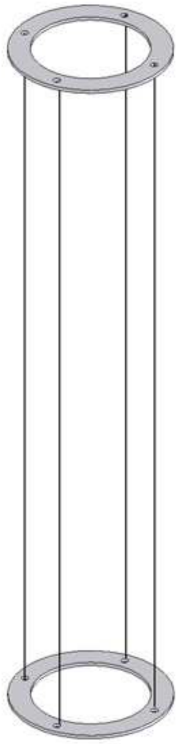

Figure 3.5: Hard plastic made by HDPE rods as the support structure, skeleton, of the support column. Connection rings are shown to how to fixed the whole structure. Dimensions are shown on technical drawings and given in appendix B with Part number 4

Figure 3.6: Rollers, would be used to rotate the endless belt between the HV and ground terminals. Dimensions are shown on technical drawings and given in appendix B with Part number 5

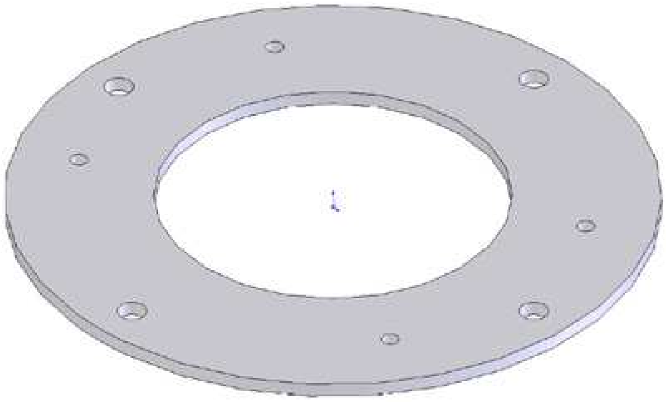

Figure 3.7: Insulator connection ring to be used to fix the lower high voltage terminal and the roller support system. Dimensions are shown on technical drawings and given in appendix B with Part number 6

roller are fixed by bearings embedded at both end, Figures 3.7, 3.8, 3.9, 3.10 and 3.11.

3.2.5 Comb-Brush Electrode

The Comb can be made from any thin or sharp pointed metal which single needle or multiple points such as brush. Comb would 3 cm in width and 15 cm in length and have 3 cm bend at the connection end to the dome and fitting hemi-sphere Figure 3.12 and 3.13

3.2.6 Belt Construction

The VDG electron carrying belt is decided as single-ply 279 cm long and 8 cm wide of a non-stretch type rubber, having a frictional constant 0.4-0.7 with the HDPE, having naturel color. The ends of the belt glued and pressed together to get an endless belt to roll between the terminals.

3.2.7 Support System Pedestal

Base should be made hard plastic or wooden. The pedestal should be made by HDPE which is hard, a good insulator and it is fire proof. All parts connected together screws shown Figure 3.14

3.2.8 Motor

For the charge conveying system a driver motor required to circulate the belt between the ground and the HV terminal. The motor speed and power

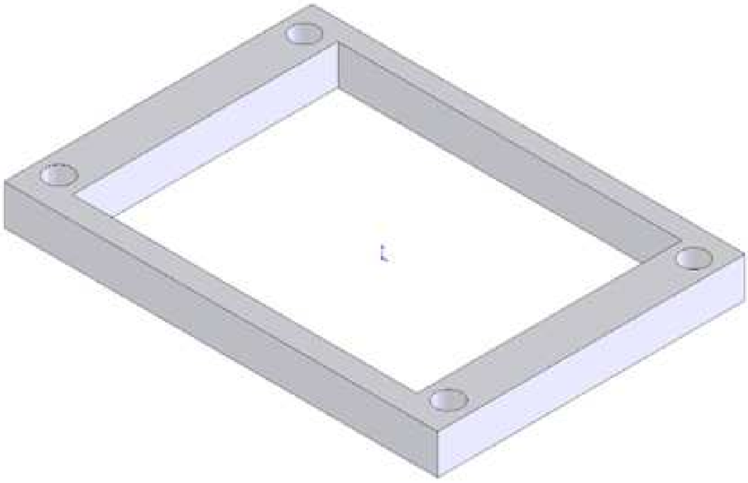

Figure 3.8: Base frame for supporting the roller support mechanism in the lower hemi-sphere of HV terminal. Dimensions are shown on technical drawings and given in appendix B with Part number 7

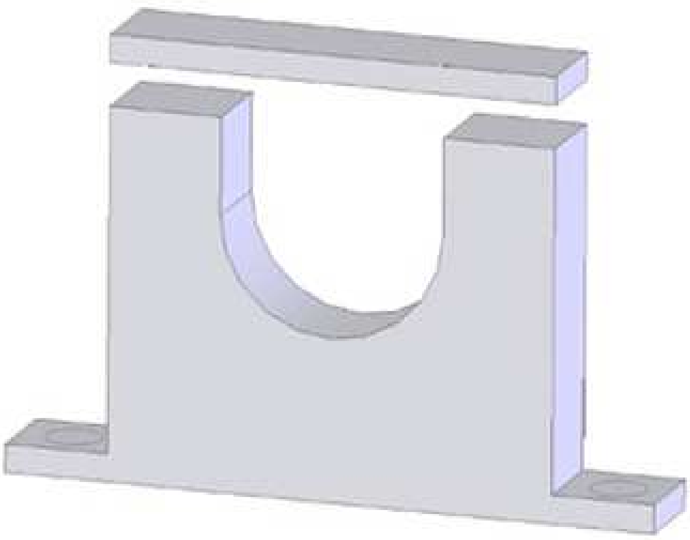

Figure 3.9: Support apparatus for the roller for embedded bearing of the rollers. Dimensions are shown on technical drawings and given in appendix B with Part number 8

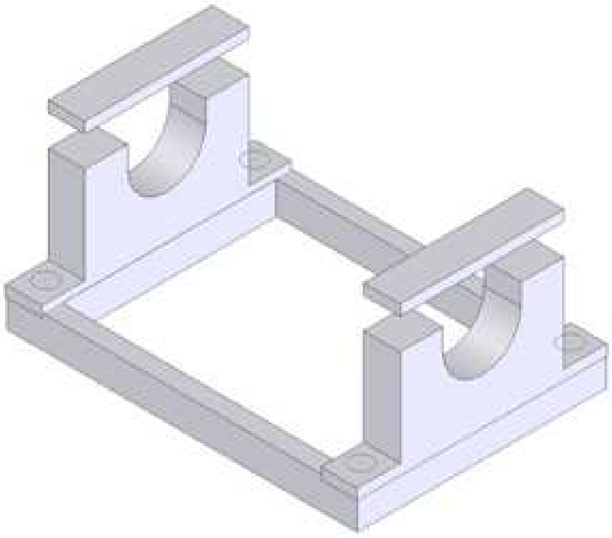

Figure 3.10: Base frame and support apparatus fixed together.

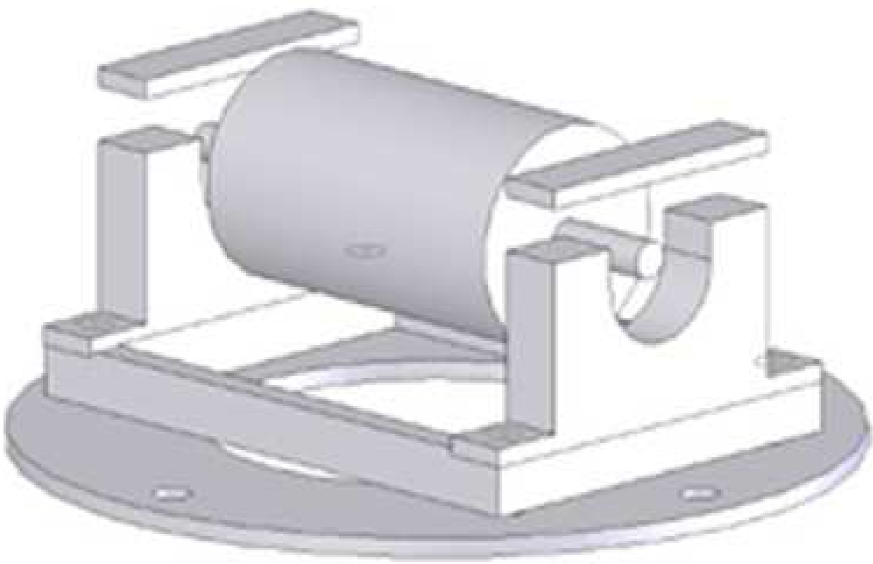

Figure 3.11: Connection ring, base frame, roller support apparatus and embedded bearing with the roller. All material are should be from insulating HDPE.

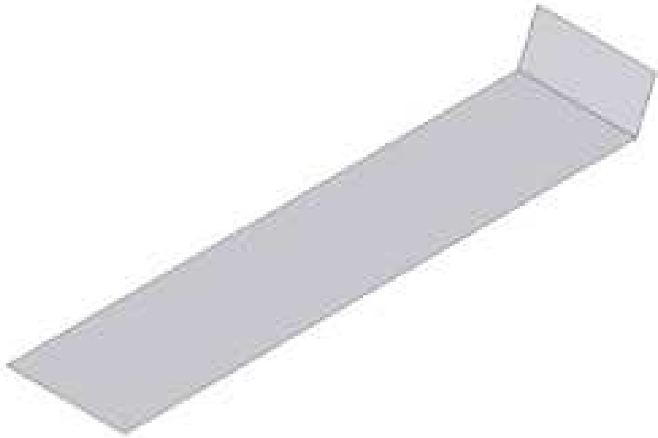

Figure 3.12: Electrode/Comb to transfer the delivered charge from the belt to the HV terminal, VDG dome. Dimensions are shown on technical drawings and given in appendix B with Part number 9

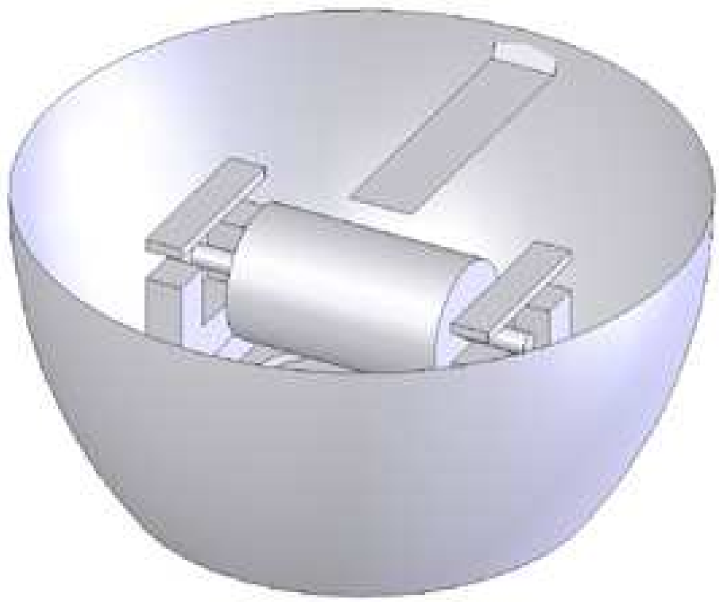

Figure 3.13: Lower hemi-spherical HV terminal with brush, roller and its support system.

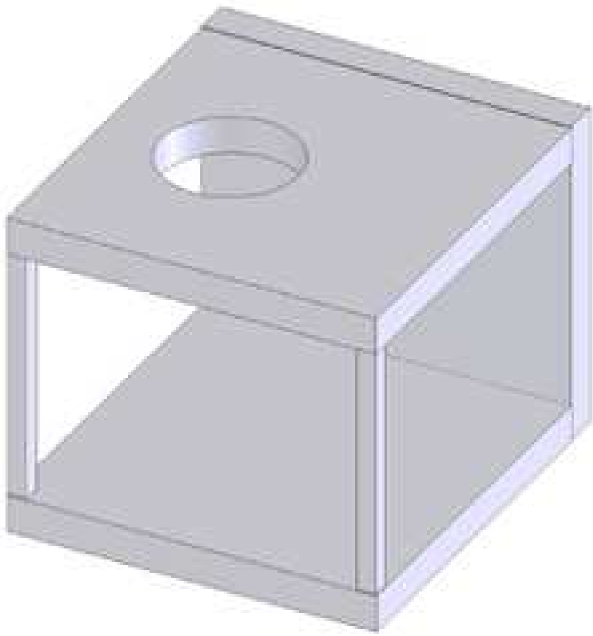

Figure 3.14: HDPE base for the pedestal of support colomn and the VDG generator HV terminal. Dimensions are shown on technical drawings and given in appendix B with Part number 10

specification could be found by using [27]

$$\frac{F_1}{F_2} = e^{f\theta} \tag{3.5}$$

where F_1 and F_2 are the tensional forces on each sides of belt, θ is the contact angle. When the set up is constructed the tensional force rate must be below 3.513 [27],

$$\frac{F_1}{F_2} = 3.513 \tag{3.6}$$

Assuming $\frac{F_1}{F_2} = 2$ then,

$$F_1 = 2F_2 \tag{3.7}$$

$$H = (F_2 - F_1)V_velocity \tag{3.8}$$

$$H = (2F_2 - F_2)V_velocity \tag{3.9}$$

$$H = F_2 \times 11.28m/\sec \tag{3.10}$$

Here, by using the possible stress 1.75 MPa [27] and the possible tensional force $= 1.75 \times 10^6 \times A = 140\ Newton$

$H = 140\ N \times 11.28m/\sec$

$$= 1529.2\ (N \times m/sec) = 1529.2\ watt \simeq\ 2\ Horse\ power \tag{3.11}$$

Therefore, the driving motor, for that purpose, could be used no more than 2 Hp. Due to the availability of monophase electric motor and required belt speed the rotation rating should 3600 rpm and have standard pillow blocks with self-aligning bearings, it also should be fireproof. The fixed inside the pedestal motor shown Figure 3.15.

3.3 Accelerating Tube

A brief description of the design of a low energy dc accelerating tube will be given in this section. This will include how the rings were made and layered together by using some epoxies or insulator adhesives, as well the flanges used and the manner in which the high voltage terminal was attached to the accelerator, the locations of possible ion or electron source, the power supply for the electron gun or ion source will also be described. A rotary pump couple with a diffusion pump system could be used the vacuum system. But it will not be discussed in detailed.

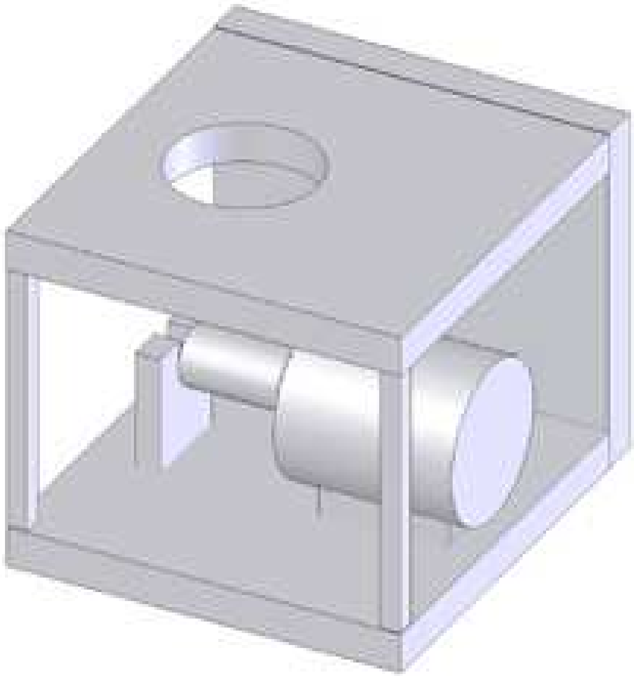

Figure 3.15: HDPE pedestal and driver Motor.

The proposed design of VDG accelerator will accelerate particle to around 270 kV which is 60 % of the electrostatic voltage accumulated on dome of the designed VDG generator. Further modifications might be required for both the position of the source and the voltage on rings by testing. Also a voltage divider system could be designed higher beam energies and intensities for a further study. One might use, is such a design, different voltages to flanges of a 5 rings of each having a group of 10 rings, in such an arrangement the potentials might be 25, 50, 110, 170 kV and finally 270 kV by a voltage divider system. But the insulator thicknesses for each 5 group of rings should be calculated and simulated by SIMION 3D.

The accelerating tube was designed to provide an electric field parallel to the tube axis to accelerate electrons from the high voltage terminal to the grounded end of the acceleration tube. The tube will be consist of equally spaced aluminum and high density polyethylene rings. At high voltages it behaves as a voltage divider, with the resistances a function of the distance between the rings and voltage V and therefore all the same. Since the current flowing down the column approximately flows through each ring, by Ohm's law there will be a constant voltage drop across each ring.

In design, a simple HV accelerator is chosen for simplicity whose insulator have equally 0,6 cm thickness and the accelerating potential is used directly to both ends of the tube. Using this idea SIMION 3D suggest around 7 kV voltage difference between could be used safely for each ring of the tube.

3.3.1 A Sample Particle Source

The electron gun or ion source, whatever chosen as the particle to accelerate should be located inside the high voltage terminal and injects electrons or ions into the accelerating tube. But the exact location of the gun or source should be determined by a matrix of experiments which is beyond our study.

In generally in most of the preliminary studies on VDG accelerates are used an old RCD 3RP1 cathode ray tube from RCA Company. Current through the filament caused it to heat up the cathode, which is a metal coated with a material having a low work function which releases electrons relatively easily.

Electrons are boiled off the cathode and repelled by the control grid of kT (where $k=8.62\times10^{-5}$eV/K is Boltzmann′s constant). A typical filament temperature is 2.250 K, making kT approximately 0.2 eV with a spread of energies described by the Maxwell-Boltzmann energy distribution. The control grid is biased according to the desired beam intensity. A negatively biased control grid reduces the intensity of the beam by only allowing electrons with energies above a

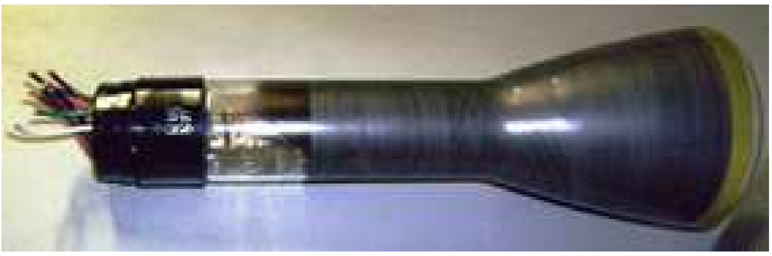

Figure 3.16: RCD 3RP1 cathode ray tube used as sample particle, electron source in the simulation of the accelerator unit in SIMION 3D (v7.0).

certain threshold to pass. A positively biased control grid will allow all electrons to pass.

3.3.2 Simulations

To verify that the presented accelerator would actually accelerate electrons or ion toward the grounded end of the accelerating tube, simulations should be done some suitable software such as SIMION 3D (version 7.0 available)to study focusing and determine the position of the cathode which yielded the smallest beam spot. The simulations might also helpful in determining the proper biasing of the electron gun and decision of the ring dimensions for aluminum and polyethylene.

To operate SIMION 3D, the accelerating potential, the locations and sizes of the electrodes and distance of the source to the tube entrance, were the input parameters as boundary conditions. SIMION 3D then used these parameters as boundary values to solve Laplace's Equations to determine the potential everywhere inside the tube and the ring dimensions for beam stability and intensity. The program approximates solutions to Laplace's equation with a finite difference technique, called over-relaxation, which is based on successive approximations [24]. In each iteration the potential of a point is estimated based on the fields of the four nearest points. One of our simulation result shown in Figure 3.17. According to the simulations the total tube length is found around 55 cm which is in a good agreement with the Van Atta and Van de Graaff's experimental design [4] having a tube length of 53 cm for 300 kV accelerating potential. The ring dimensions using the results of SIMION 3D and the construction of the whole system will be explained in following sections.

3.3.3 Equipotential Rings

A approximately 270 kV (60 % of the VDG generator voltage) used as accelerating potential as the first parameter for the simulation. 3 mm for thickness

4 cm inner radius and 11 cm for outer radius for the accelerator rings then used as another set of input data. Finally, the polyethylene ring dimension as 6 mm for thickness, 5 cm for inner and 10 cm for outer radii, are used as insulator ring parameters for the SIMION 3D

After simulations of above input data and sample particle source RCA3RP1 55 conducting electrode rings and 56 insulator rings suggested by SIMION and 5 kV taken as the potential each electrodes as the potential could be applied without any risk for the accelerator unit.

The accelerating tubes equipotential rings by aluminium designed with flanges for later needs, such as the voltage divider principle, and high density polyethylene rings are designed as shown in Figure 3.18 and 3.19 and the technical drawings presented in appendices B. One should note that all the rings were identical, in terms of the four smaller holes since they would be aligned on all insulator and accelerating electrodes.

A schematic view of the assembled accelerator tube design with conducting metal electrodes and insulating rings as given in Figure 3.20 and 3.21. Note that the flanges are ready for connection for voltage divider system. For later modifications the approximately length would be around 55 cm due to the adhesives thickness. As emphasized before this length for 275 kV is in a good agrement with the one given [4] for 300 kV

3.4 Vacuum System

A vacuum system for the low energy VDG linear accelerator and even for the generator would be useful to get the highest efficiency, especially for the linear accelerating tube. It is generally used a rotary pump as a fore-pump and a diffusion pump coupled together to get 10^{-4}-10^{-6} torr for the vacuum system in experimental designs [28].

The vacuum system will be the most expensive part of the presented design. The approximate cost would around with the best intention, many times doubling (plus the insulation costs, unfortunately) the total cost of the whole VDG generator and accelerator system.

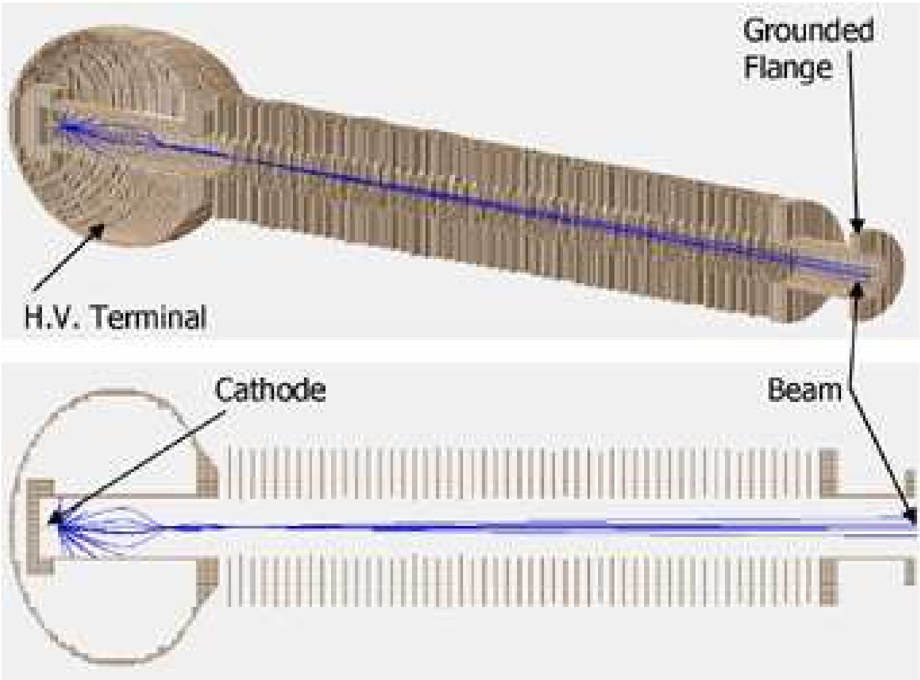

Figure 3.17: SIMION 7.0 simulation of the accelerator for a sample particle source RCA3RP1 cathode ray tube and for designed rings. The high voltage terminal is not to scale due to computer memory limitations and screen resolutions.

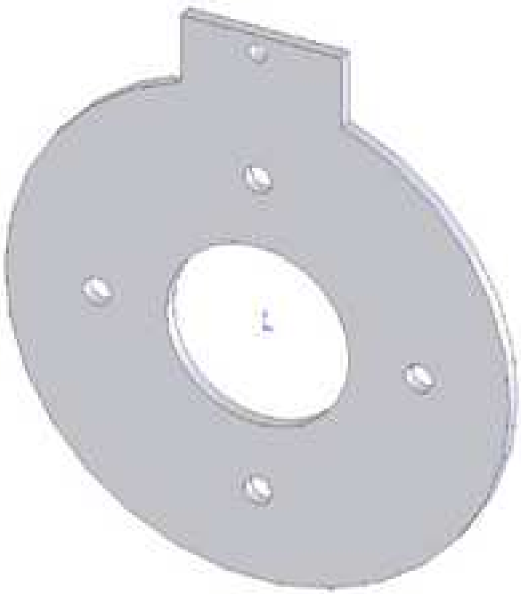

Figure 3.18: Conducting, probably aluminum-5052 composition, equipotential electrode ring with flange for the accelerator tube. Dimensions are shown on technical drawings given in appendix B with Part number 11

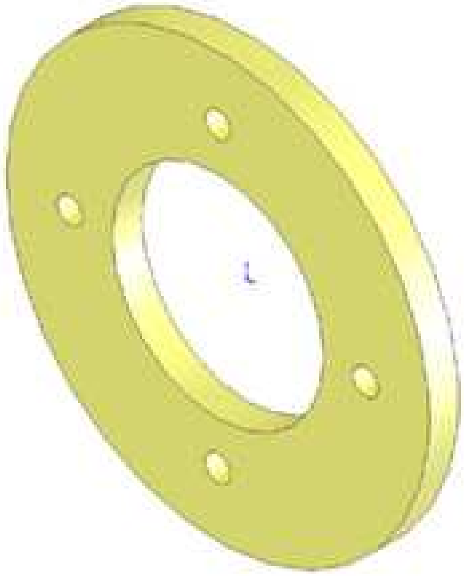

Figure 3.19: Accelerator insulator polyethylene ring. Dimensions are shown on technical drawings and given in appendix B with Part number 12

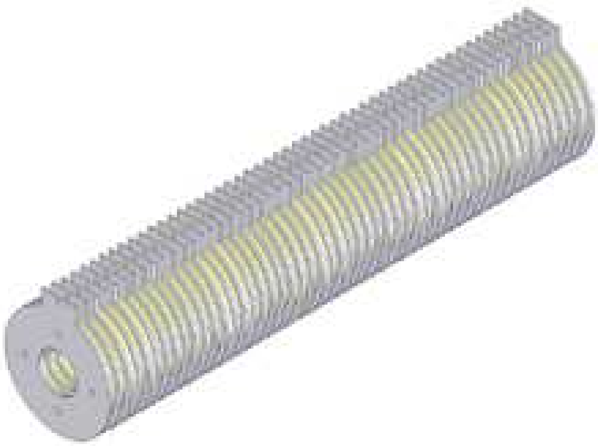

Figure 3.20: Accelerator tube

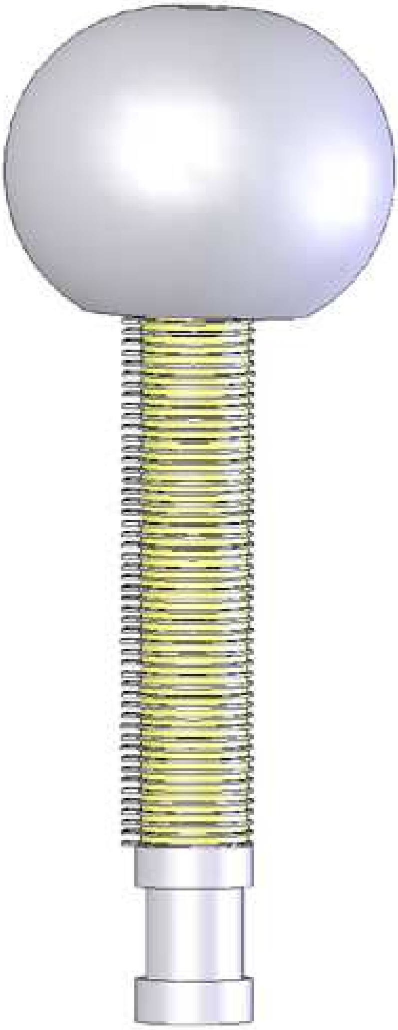

Figure 3.21: Accelerator tube as attached to the HV sphere. A connection flange or a "T" flange could be used at the end depending on the use of vacuum system

CHAPTER 4

CONCLUSION

In this work the design procedures of a small low energy Van de Graaff generator and accelerator system has been described and carried out, as possible, for all parts of and the units as shown Figure 4.1

The accelerator part of the VDG unit has been modeled with SIMION 3D [25] and some design parameters for the accelerator and particle source are taken from these simulation result of the software. According to the simulations the total tube length is found 55 cm for 275 kV (which is 60 generator voltage) which is in a good agreement with the Van Atta and Van de Graaff's experimental design [4] having a tube length of 53 cm for 300 kV accelerating potential.

For a further study, the VDG generator unit and then the VDG accelerator unit should be constructed separately using the presented technical drawings of the parts of the VDG generator and accelerator as explained.

The VDG generater should be tested for the desired accumulated voltage by careful experiments. The desired voltage rating could be achieved by increasing or decreasing the spraying voltage supplied by a HV transformer. The accelerator system also should be tested by careful matrix of experiments for the exact location of the particle source, potential ratings for the rings and accelerated particle energy by the measurement of Bremsstrahlung (stoping - breaking radiation) x-rays energy spectrum. Also the particle source and the source the tube distance should be recalculated for a further study.

The VDG generator and accelerator system could be used to study simple nuclear reactions, nuclear structure, material science and x-ray production experiments, in its energy range, in small labs and in educational studies of student labs, paying attention to the static HV sparks and breakdowns in the environment.

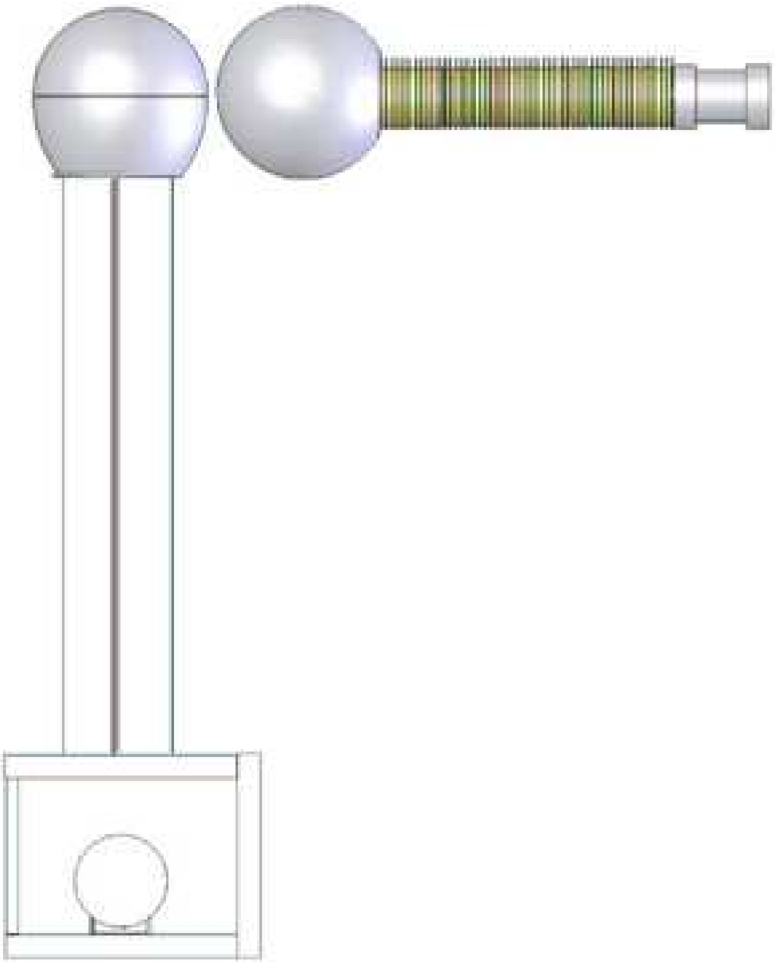

Figure 4.1: VDG generator and accelerator units. The spheres should be in contact when the required acceleration potential is reached and the acceleration is in progress.

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APPENDIX A

PART LIST

A.1 VDG Generator Part List

Part Name For Vdg Generator	Quantities
Hemi-Sphere Copper HV Terminals	2
Connection hard plastic rings for the column	2
Hard plastic rods for column	4
Roller for the belt circulation	2
Ring for roller and dome connection	1
Roller support base	1
Roller put base	3
Hard plastic lower base - pedestal	1
screws (around)	40

A.2 VDG Accelerator Part List

Part Name For Accelerator	Quantities
Hemi-Sphere Copper HV Terminals	2
Accelerator Metal Rings	55
Accelerator Insulator Rings	56
Insulator rods to attach the rings	4
Normal or "T" flange	1

APPENDIX B

TECHNICAL DRAWINGS LIST

B.1 VDG Generator Technical Drawings List

Part 1 : Hemi-sphere
Part 2 : Hemi-sphere open
Part 3 : Connection hard plastic rings for fixing the support column
Part 4 : Skeleton of the support column
Part 5 : Roller
Part 6 : Insulator connection ring between column and dome
Part 7 : Insulator connection between dome and roller base
Part 8 : Roller base at dome
Part 9 : Electrode/Comb
Part 10 : Base from Hard Plastic-HDPE

B.2 VDG Accelerator Technical Drawings List

Part 11 : Equipotential electrode ring
Part 12 : Insulator ring
Part 13 : Normal connection flange

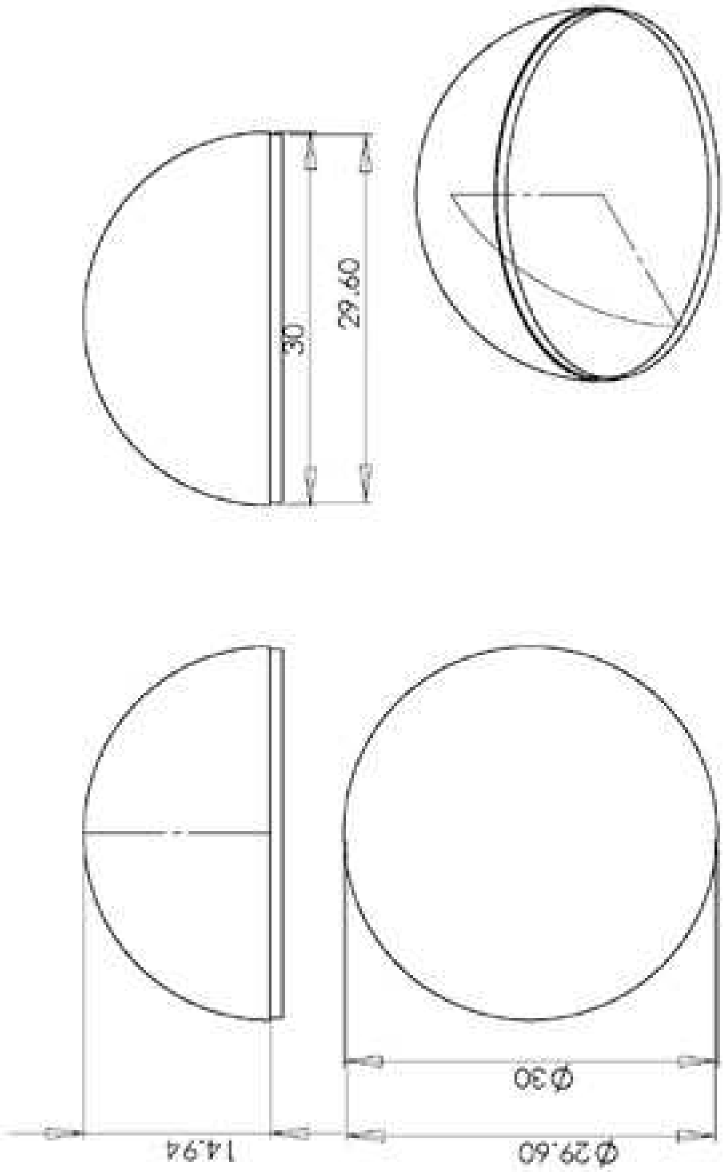
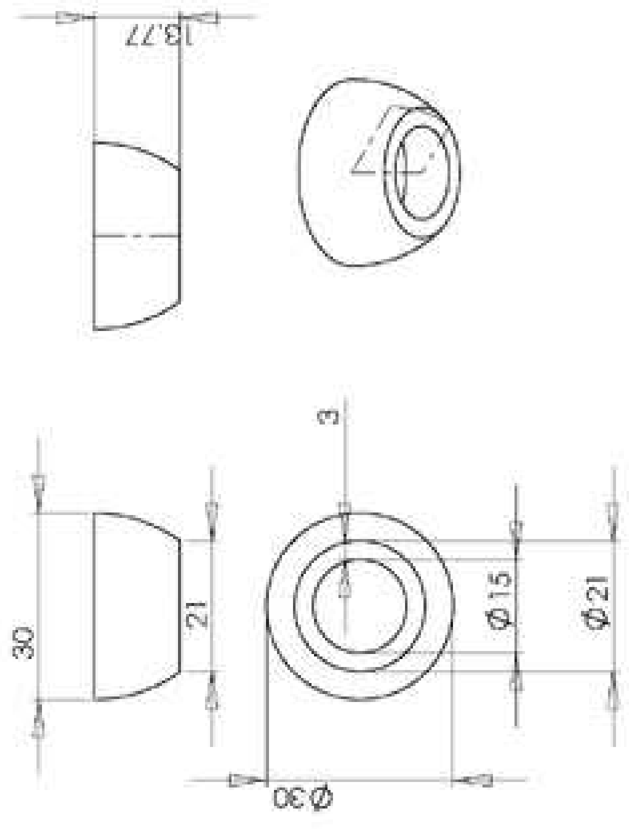


Figure B.1: Part 1



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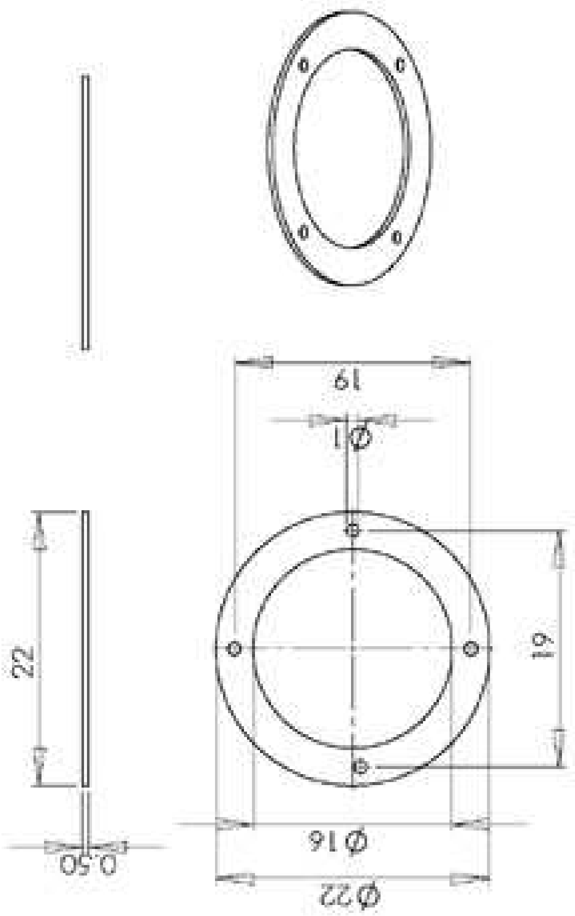

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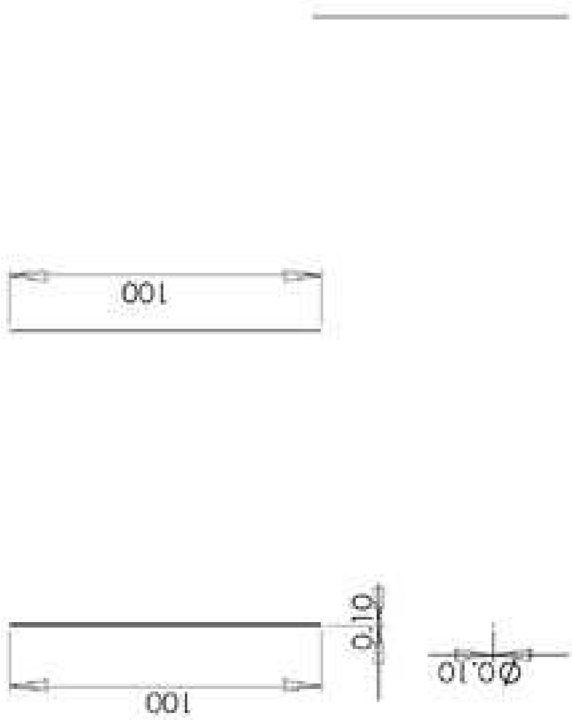

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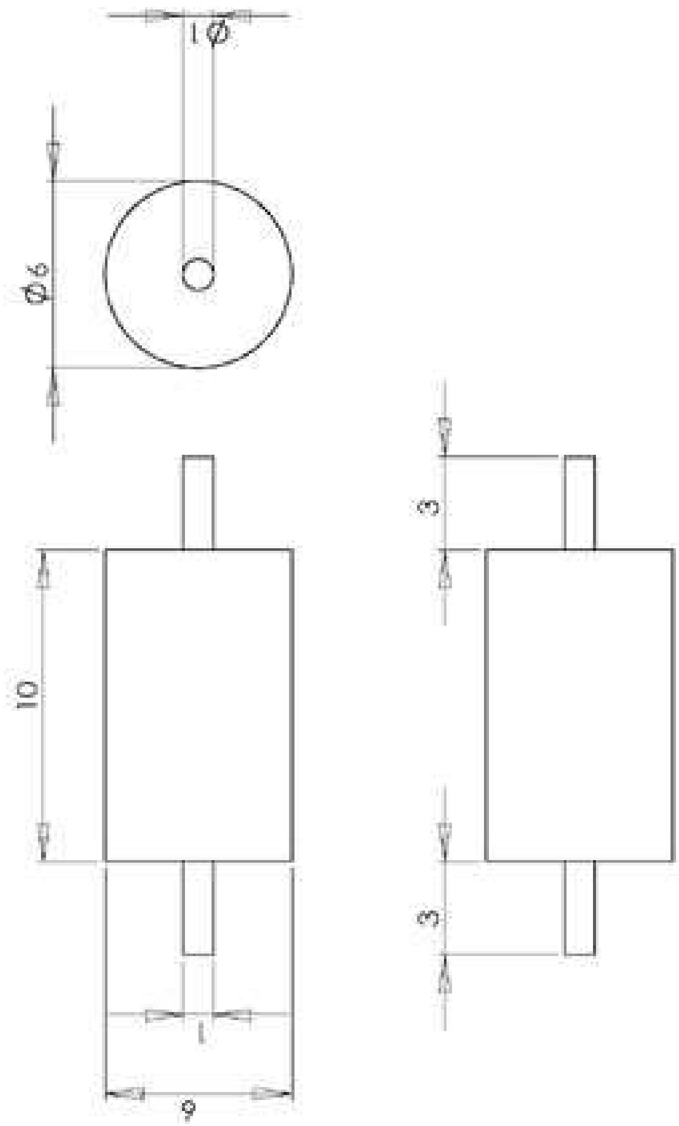

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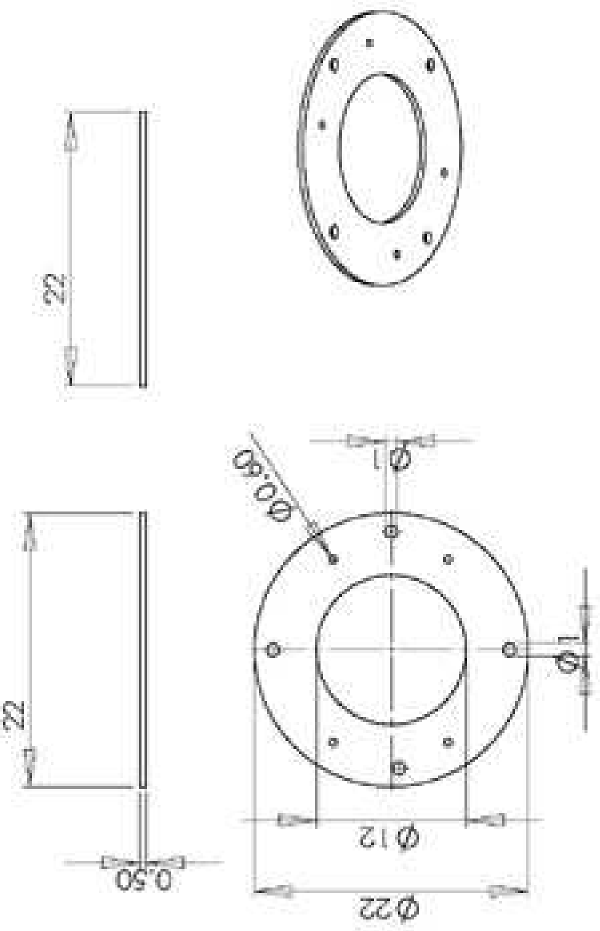

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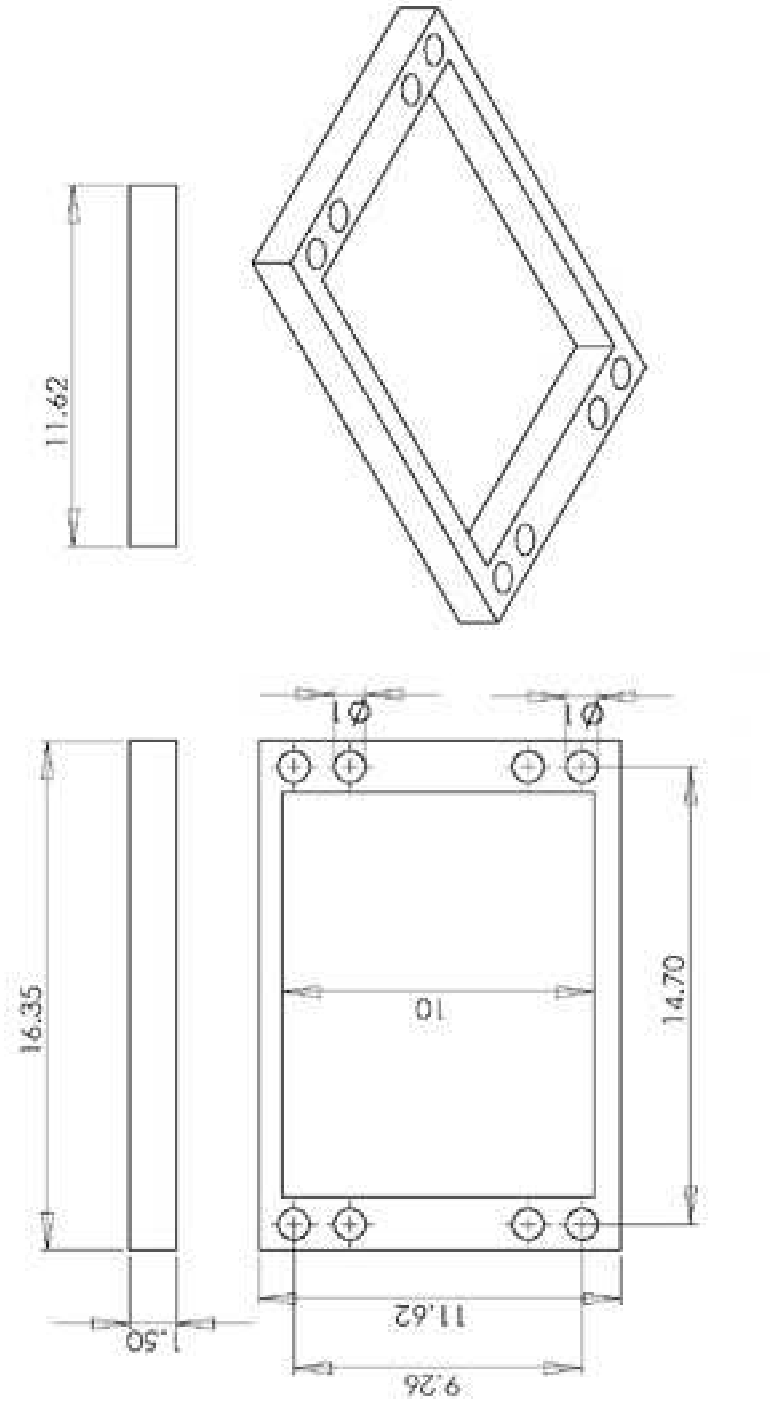

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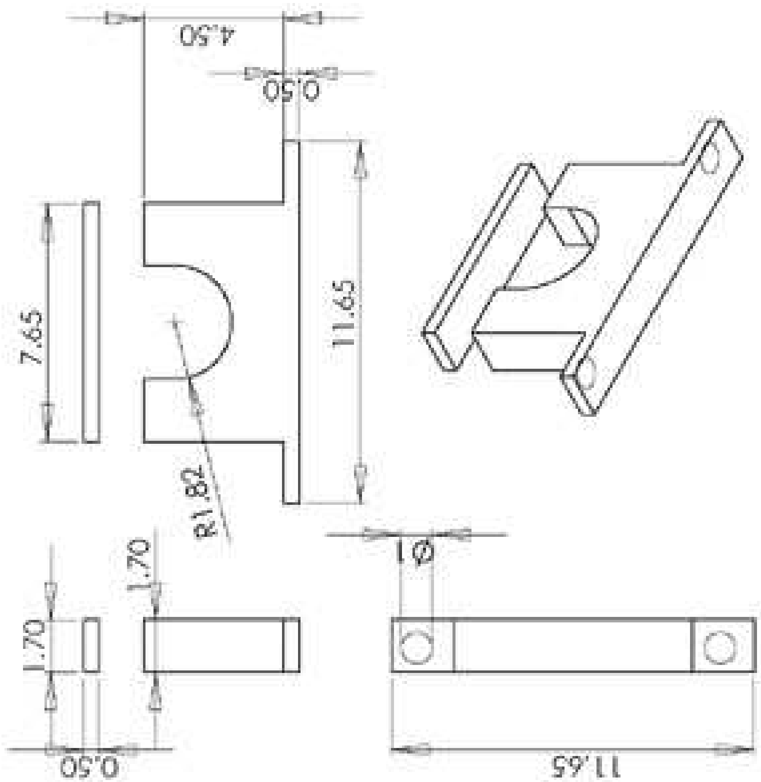

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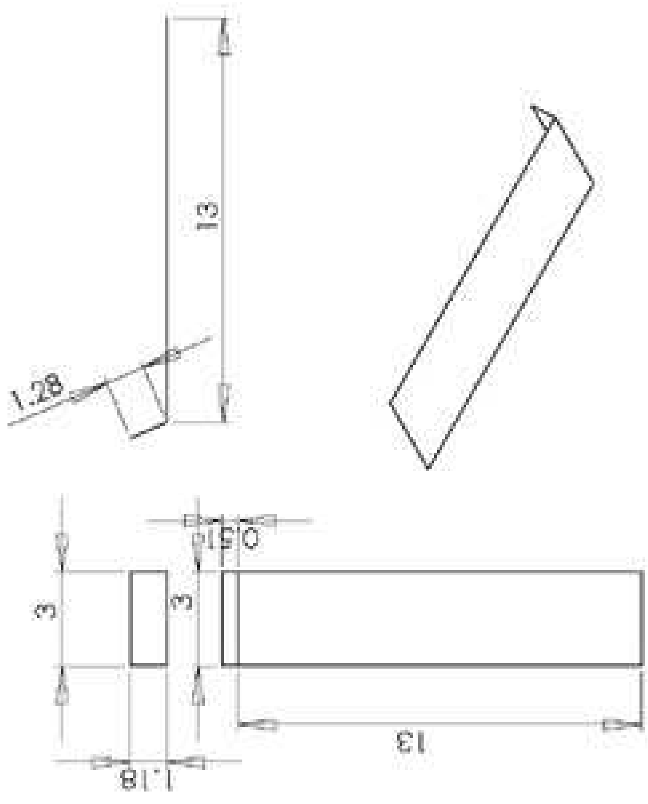

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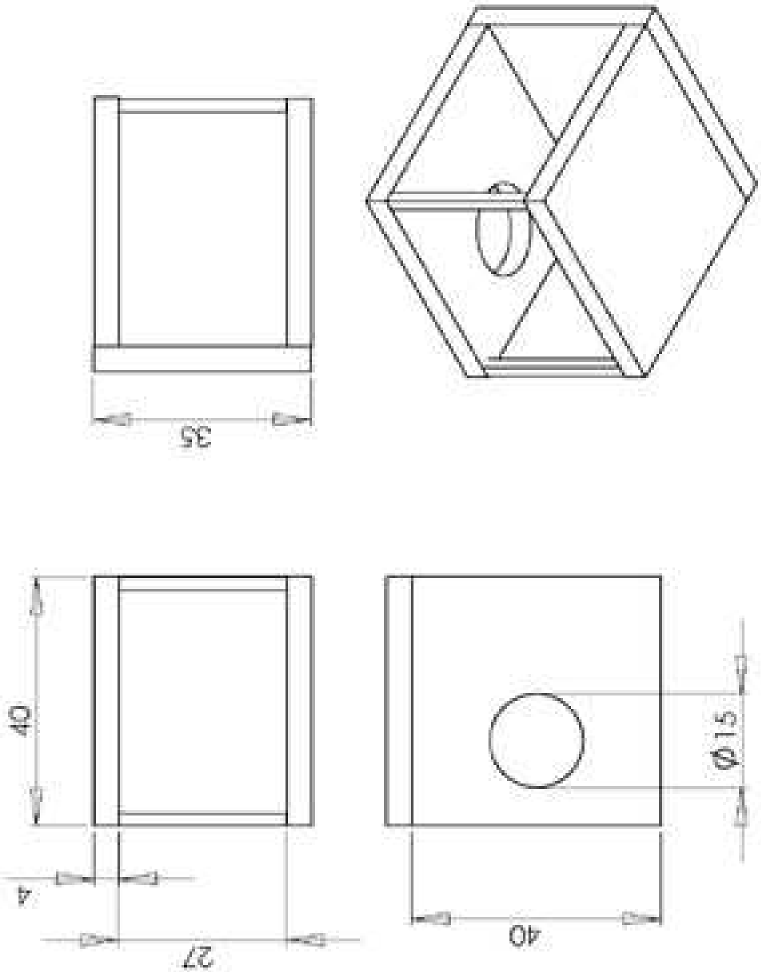

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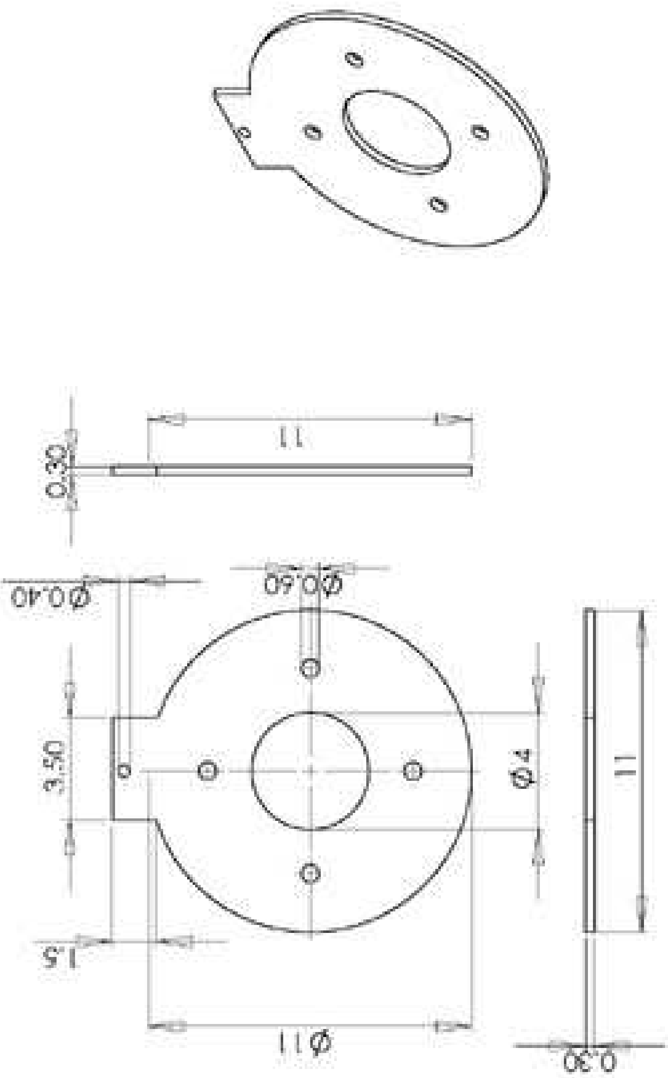

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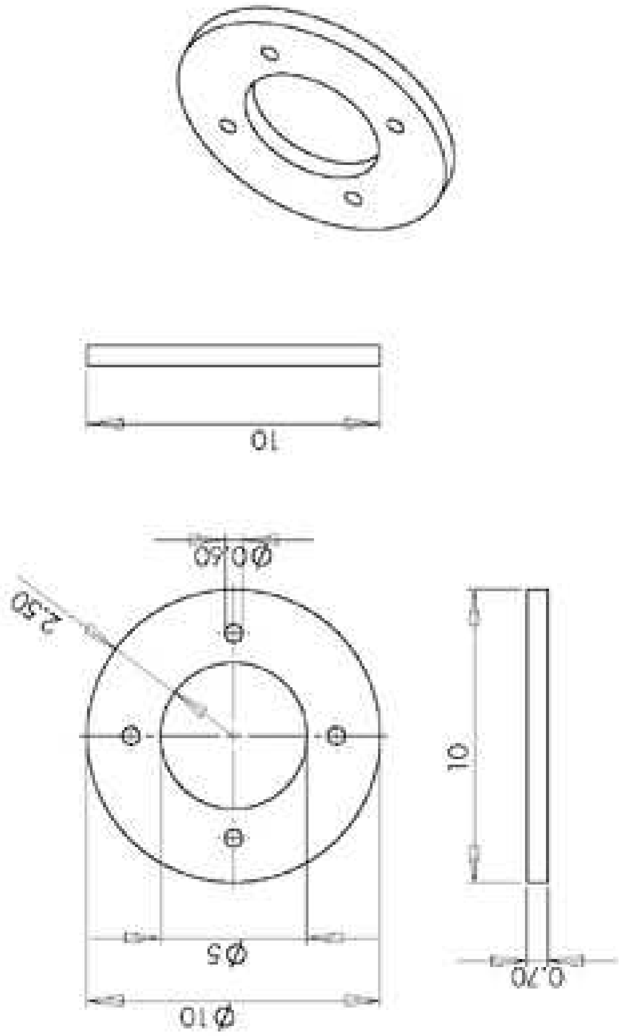

Figure B.12: Part 12

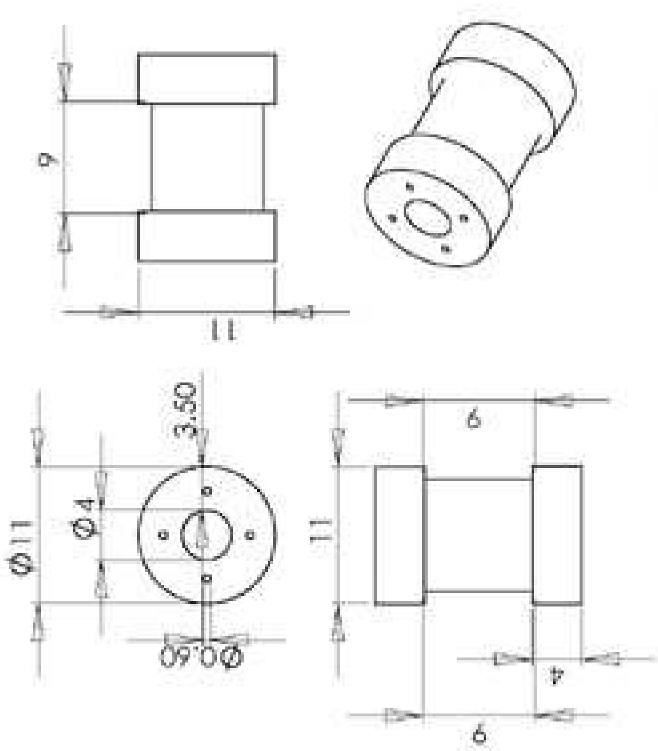

Figure B.13: Part 13

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