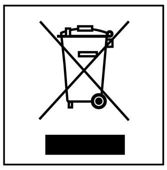
Van de Graaff Generator

Purpose

This motor driven version of the classic Van de Graaff Generator creates electric potentials up to 200kV. The moving belt transfers electric charge to the rounded dome creating a source of high voltage static electricity, ideal for demonstrating and exploring the phenomena and principles of electrostatics.

WEEE directive

This symbol indicates that the electronic equipment should not be disposed of in the normal waste. It should be recycled in accordance with the WEEE directive.



INDOSAW

Basic electrostatics

An **electric current** is a **flow of electrons** through a conducting material, e.g. copper or aluminium. The electrons move when a potential difference is applied to the conductor, and the current stops when the potential difference is removed.

Static electricity is typically the accumulation of electrons on a non-conducting material, e.g. a plastic. Friction between certain materials, e.g. glass and silk, results in the transfer of electrons from one to the other. One loses electrons and becomes positively charged, the other gains electrons and becomes negatively charged. Because the two materials are non-conductors (insulators), the **charge cannot move**, it is static and remains on the materials, until it leaks away by contacting other objects.

When objects acquire a static charge, they have either lost or gained electrons.

Electrons are small negatively charged particles which are an essential component of all atoms.

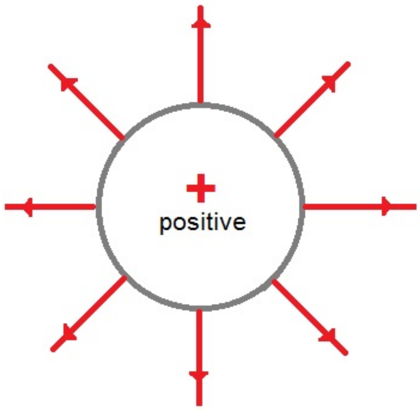
If an atom or molecule loses electrons, it becomes a positive ion.
If it gains electrons, it becomes a negative ion.

A simple rule to remember: **Like charges repel** **Opposite charges attract**

A charged object has an electric field around it.
Any charged particle or object in an electric field experiences a non-contact force.

The arrows in the field show which way a positive charge would move.

The field around the Van de Graaff Generator dome is a **radial field,** it extends in all directions.

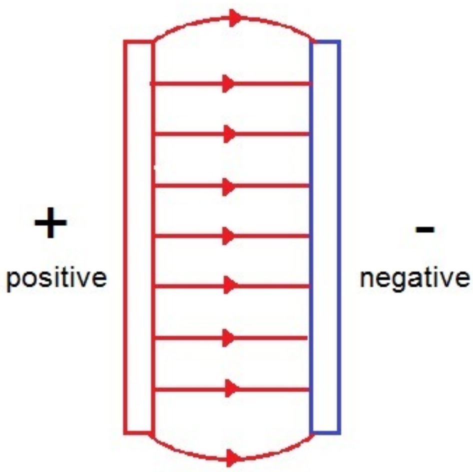


Between oppositely charged plates, there is a **uniform electric field**.

It can be imagined as parallel lines from the positive plate to the negative plate.

Actually, a uniform field is created whenever the plates are at different potentials, e.g. +200 V and 0 V or +200 V and +100 V or 0 V and -75 V
There must simply be a potential difference.

Again, the arrows show the way a positive charge would move, but the lines are imaginary and have no other meaning.



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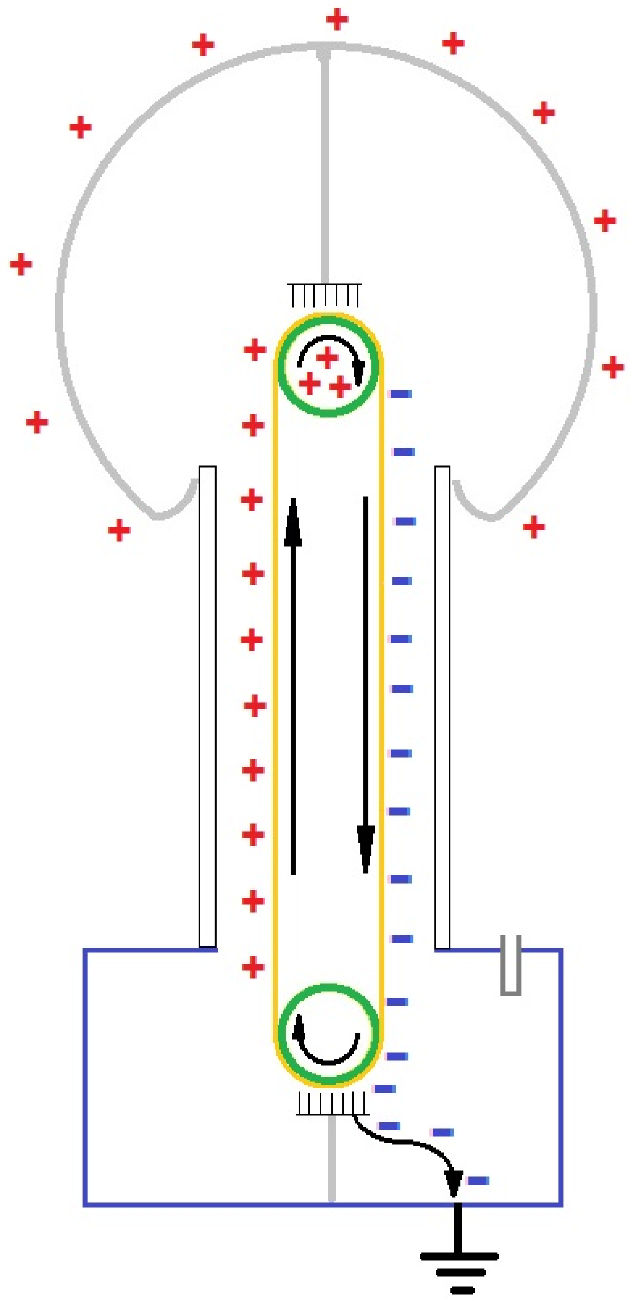
Inside the Van de Graaff Generator



In the Van de Graaff Generator, the metal dome is supported on an acrylic tube, so it is insulated from the earthed metal base.

The rubber belt runs on acrylic rollers. As the belt separates from the upper roller, it takes electrons with it. The comb is connected to the dome and has the effect of "spraying" electrons on to the belt. The dome loses electrons and the electrons are carried away on the belt.

At the bottom roller, electrons are lost via the earth connection in the base, the moving belt becomes positively charged and continuously collects electrons from the dome, so the positive charge on the dome increases.

The metal dome is not connected to earth, so the accumulated positive charge is stored until it finds another way to escape.

The "earth" connection in the base is literally to planet Earth, which is large enough to absorb the electrons being removed from the dome.

An earth connection is also called "ground" and is effectively at 0 volts.

The Van de Graaff Generator must be connected to the mains via the 3 core mains lead supplied, so that it is reliably earthed.

The case of the Van de Graaff Generator has a 4 mm socket which is earthed.
The main use of the socket is to support the discharge ball and connect it to earth.

Mains input

Mains input is via an IEC socket, which has an integral fuseholder. The fuse carrier can be opened using a flat bladed screwdriver, and the carrier contains a spare.

The fuse is a 1 A time delay or slow-blow fuse, marked T1A 240V.

VdGG and accessories

For convenience, these notes will use the abbreviation VdGG to refer to the generator.

Accessories

The following accessories are included with the Van de Graaff Generator:

The items fitted with a 4mm plug * can be mounted in the socket on the top of the generator's dome.

1. Acrylic rod * with light ball ('pith ball') attached by a non-conducting thread
2. Faraday's Pail * - the acrylic rod will also plug into the 4mm socket inside the pail
3. Acrylic cylinder * with a metal base and cap, containing four light pith balls
4. "Head of hair" *
5. Point discharger *
6. Electric spinner (Hamilton mill) and needle point * - a small rubber stopper is provided for safe storage of the sharp needle
7. Neon bulb with wire soldered to the centre contact
8. Reel of non-conducting thread

Caution: anyone who has a pacemaker, an implanted hearing device (Cochlear implant), heart condition, or wears hearing aids should take great care to avoid getting shocks from the VdGG. People can be affected and devices may possibly be damaged by receiving sparks from the VdGG.

VdGG experiments

Electromagnetic Compatibility Regulation (EMC) 2005

The use of the Van de Graaff Generator outside the classroom or laboratory invalidates conformity with the protection requirements of the EMC Directive and could lead to prosecution.
The VdGG, in normal operation, generates frequent brief high energy electromagnetic pulses which can affect sensitive electrical equipment nearby.
This effect should not extend beyond the generator's immediate environment (room or laboratory).

Basic operation

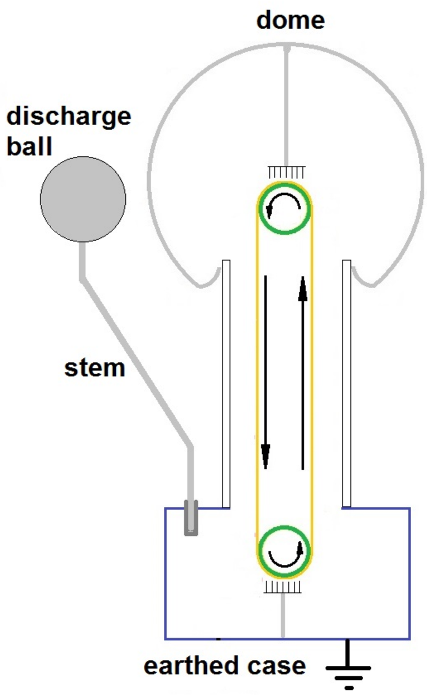
When any experiment is finished, switch off the generator and move the discharge ball so that it contacts the dome and discharges it. This simple precaution should greatly reduce the risk of shocks.

Charge and discharge

Check the VdGG is switched off. Plug the discharge ball into the 4 mm socket on the case and check that the ball can be moved freely.
Adjust the position of the discharge ball, to make a gap of about 20 mm between it and the dome.
Switch on the VdGG. The moving belt quickly charges the dome and sparks will jump the gap.
The discharge ball and stem are connected to earth, so you can safely touch them.
Increase the gap slowly to the maximum, about 60 mm, by turning the stem in the socket.

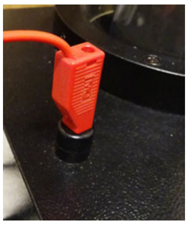
How do the sparks change? Can you explain why?
Watch the discharge ball carefully. Explain what you see.

Don't forget to switch off and move the discharge ball to touch the dome.



Feel the force

Connect a long 4 mm plug lead to the earth socket on the case.
Connect the other end to the 4 mm plug on the stem of the discharge ball.
NOTE: it must be a stackable plug.



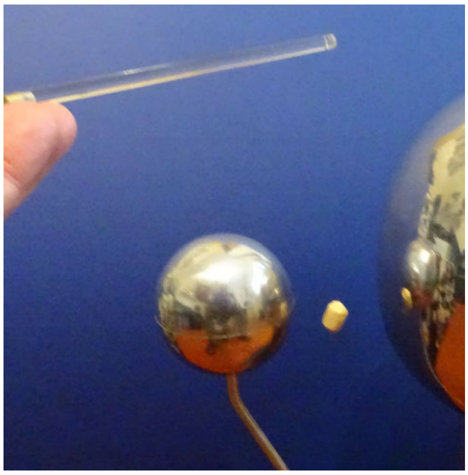
Hold the stem of the discharge ball *lightly* between fingers and thumb.
Begin with the discharge ball at least 200 mm (20 cm) away from the dome.

Switch on the VdGG.
Bring the ball steadily closer until a spark jumps the gap. Keep the ball at that distance.
Feel what happens as the sparks jump. Explain what you feel.

Switch off the VdGG. Discharge the dome by touching it with the discharge ball.

VdGG experiments

Which way is the charge going?



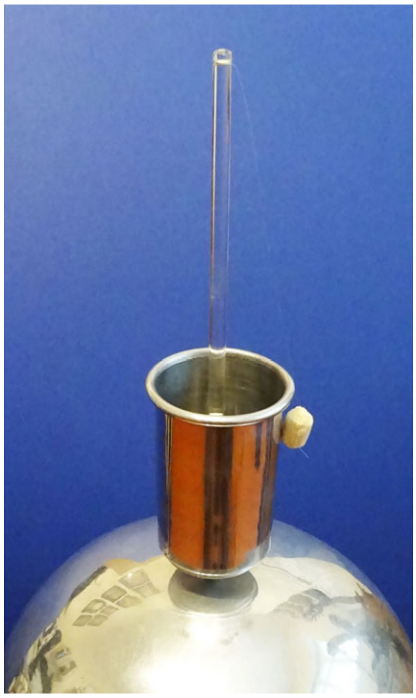
Keeping your hand near the discharge ball, dangle the pith ball in the gap between the discharge ball and the dome.

Switch on the VdGG.

The ball dances to and fro.
It is taking charge from one side of the gap to the other.

Can you work out which way the charge is moving?
The dome is positive because it has lost electrons - does this help?

Faraday's pail



There are two stages to this experiment:
1 Fit the Faraday pail to the top of the VdGG dome and plug the acrylic rod with attached pith ball into the 4 mm socket inside the pail.
Remove the discharge ball and put it to one side.
Make sure the pith ball is **outside** the pail.

Switch on the VdGG.

The pith ball swings away from the pail - it is repelled.
What charge must be on the ball?

AVOIDING the dome, point a finger towards the pith ball.
Explain your observation, remembering that you are standing on the floor, which is probably close to earth potential (0 volts).

Switch off the VdGG.
Carefully fit the discharge ball to the earth socket and move it towards the dome to discharge it.

2 Put the pith ball **inside** the Faraday pail. Remove the discharge ball.
Switch on the VdGG.
What do you observe?

Faraday discovered that there is no charge inside a metal container, such as the pail. The charge is all on the outer surface. Can you now explain the behaviour of the pith ball?

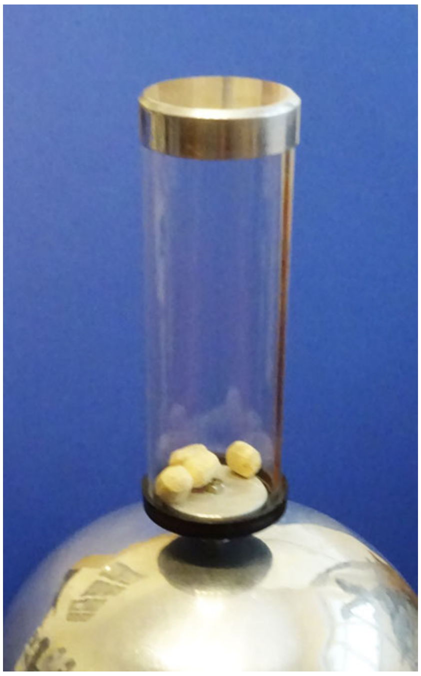
Switch off the VdGG.
Carefully fit the discharge ball to the earth socket and move it towards the dome to discharge it.

Based on this discovery, look up a "Faraday Cage" and find out what it is used for.

Perhaps you can explain why it is safe to be inside a car during a thunderstorm.

VdGG experiments

Conduction?



Attach the acrylic tube with metal caps to the top of the VdGG dome.
The four pith balls are initially in contact with the internal metal disc.
Remove the discharge ball and put it to one side.

Switch on the VdGG and observe the pith balls for 30 seconds.

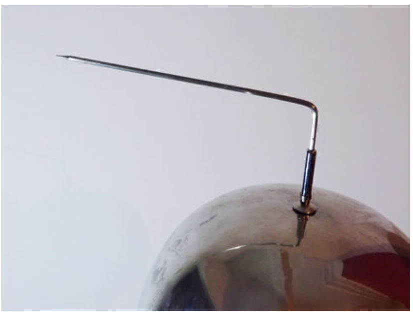
Avoiding the dome, bring a finger near to the metal top cap.
Explain the change in behaviour of the balls. What do you feel?

Move the finger further away then bring it back.
How does the behaviour change?

You are in contact with the ground (earth) and can therefore supply electrons, through your body, to the top cap of the acrylic tube.
Why do the balls go down the tube, when your finger is near the top cap?

Switch off the VdGG.
Refit the discharge ball and discharge the dome.

Feel the breeze!



Fit the point discharge accessory to the top of the VdGG dome.

Remove the discharge ball and put it to one side.

Switch on the VdGG.
Bring the back of your hand close to the sharp point - about 20 mm.
What can you feel?

To show that it is not an imaginary effect, light a candle and bring it near the point. Move the candle until you see the flame being affected.
It is possible to blow out the candle in this way.

The charge density at a point is very high. You could imagine that the charge is being "sprayed" into space.
Remember that the dome and the metal point are positively charged.

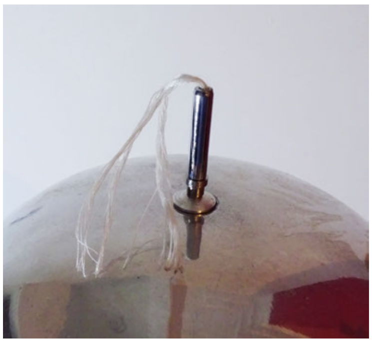
Air molecules near the point lose electrons - the electrons move to try to cancel out the positive charge on the dome. As the air molecules lose electrons, they become positively charged ions and are repelled by the positive charge on the point. The air molecules rushing away produce the "breeze" that you felt.

Move the candle away and switch off the VdGG. Wait 10 seconds.

Touch the dome. Why do you not receive a shock?
What has happened to the charge on the dome?

VdGG experiments

Head of hair



Attach the "head of hair" accessory to the top of the dome.
Remove the discharge ball to one side.

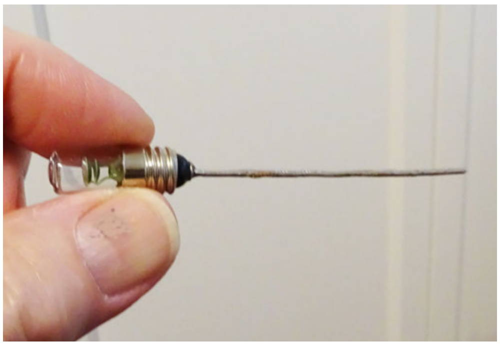
Switch on the VdGG.

The "head of hair" becomes positively charged and the individual strands repel each other.
AVOIDING the dome, point a finger towards the strands.

Electrons from the finger are attracted to the positive ends of the hair, the human body conducts and acts as a path for electrons to move from the ground/earth towards the positive charge on the hair and the dome.
NOTE: To keep the head of hair in good condition, avoid touching the strands with greasy fingers.

Making gases conduct electricity

Adjust the position of the discharge ball to leave a large gap between it and the dome.



Switch on the VdGG.

Hold the neon bulb as shown and point the metal spike towards the dome from about 200 mm away. Look closely at the neon bulb as you bring the spike closer to the dome.

Inside the bulb are two separate metal discs, one connected to the spike, the other connected to the metal body. The glass bulb is filled with neon gas, which conducts electricity and glows orange.

Once again, the human body is acting as a conductor, supplying electrons through the neon gas to the spike and then to the dome.

Notice that the VdGG does not produce any sparks while the neon bulb is lit.
The charge is being neutralised by the electrons coming through the neon.

Switch off and discharge the VdGG.

Let there be light

A fluorescent tube has metal end caps and contains a a small amount of mercury vapour.

Hold a fluorescent tube by one end, above, but not touching, the VdGG dome.

Switch on the VdGG and observe the fluorescent tube.

Switch off and discharge the VdGG.

VdGG experiments

Hamilton's mill

Fit the needle mounted on the 4mm plug into the top of the VdGG dome.
Rest the spinner's centre on top of the needle - check that it rotates freely.
Remove the discharge ball and put it aside.

Switch on the VdGG.

Explain the movement of the metal spinner.

The spinner is positively charged, like the dome.
Each point has a strong electric field around it. Air molecules close to the points lose electrons and become positively charged ions - their electrons were attracted to the points and used to neutralise some of the charge on the dome.

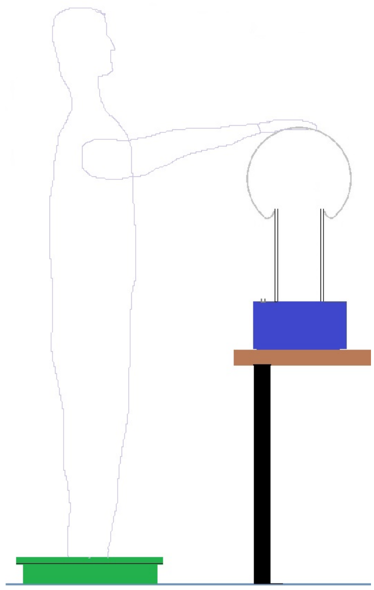
Positively charged ions are repelled by the positive spinner's points and move away. The points move in the opposite direction (Newton's 3rd law) so the spinner rotates.

Making hair stand on end

The ideal subject for this experiment has long hair, around shoulder length, that has been washed recently. Gel or hairspray will spoil the experiment.

A person with a pacemaker, Cochlear implant or heart condition must not take part.

For the best results, place the VdGG near the edge of a table or bench. Have a wooden metre rule handy.



Place an empty, dry Gratnell (or similar) tray on the floor in front of the VdGG, about an arm's length away from the VdGG dome.

Remove the discharge ball and put it aside on the bench.

The person to be charged stands in the Gratnell tray and is therefore insulated from the earth. For reasons they can be asked to explain, they should remove any sharp pointed jewellery or watches.

With one hand by their side, they put their other hand on top of the dome.

Switch on the VdGG.

The person should describe what they feel and shake their head to help their hair to spread out. Depending on the weight of the person's hair, the effect can be spectacular!

Try pointing a finger at the ends of the person's hair. What happens and why?

The charged person can lift their hand from the dome for a few seconds and replace it.
Why don't they get a shock?

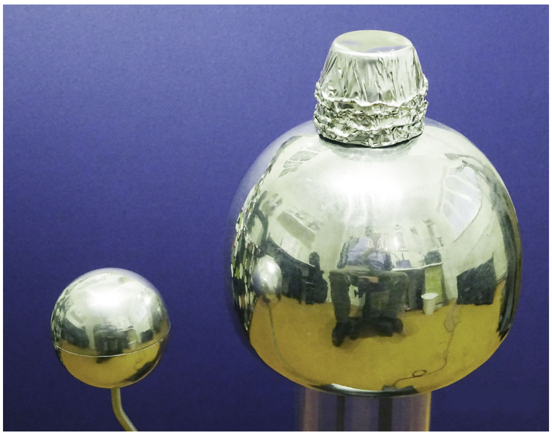
Switch off the VdGG. Why does the person's hair stay spread out?

If the charged person steps out of the tray, they usually feel a slight shock as they discharge to earth.
Alternatively, they can get hold of a wooden metre rule held by another person, then step out.

Feel the inside of the Gratnell tray - some charge remains on the non-conducting plastic tray.

VdGG experiments

We have lift off!



Stack 5 or 6 small aluminium foil pie cases on top of the dome.
They should be inverted.

Leave the discharge ball in position, at the maximum gap of about 60 mm.

Switch on the VdGG.

Expalin the behaviour of the pie cases.
Remember that aluminium is a conductor.
Why do they lift off one at a time?
When does the VdGG produce sparks, and why?

Blowing bubbles

This suggestion will require considerable care.

You need a battery operated bubble generator, small enough to sit securely on top of the VdGG.
It can be held in place using Blu-Tack.
Precautions against spillage of the bubble liquid must be taken.
Ideally, the bubbles should leave the bubble generator in a vertical stream.

First, set the bubble generator going. Observe the movement of the bubbles.

Switch on the VdGG.

Do the bubbles behave differently? Why?
Do all the bubbles behave the same? How high do the bubbles go?

Pointing a finger at any bubble should draw it towards the finger. Why?

Bubble dynamics

A coulombmeter with charge plate, held in the hand, can be used to capture the bubbles.
Counting the bubbles as they land on the coulombmeter's charge plate can provide a mean charge per bubble. See page 11 for an estimate of the total charge on the dome.

Operating the bubble machine on an electronic balance (away from the VdGG) should give a mean mass per bubble.

From the mass and motion of a bubble, is it possible to calculate the force acting on the bubble?

If the force is a result of electrostatic repulsion, how is this related to the charge on the bubble and the VdGG's potential?

VdGG advanced electrostatics

The maximum voltage is limited by the radius of the dome, and leakage from it.

This VdGG produces sparks up to 60 mm long, between the earthed discharge ball and dome.
Using the rule of thumb 3 kV/mm this gives a potential of 180 kV on the dome.

The dome's radius is 10 cm or 0.1 m.

The dome has an electrical capacitance, C, of approximately 2 picofarad (2 pF), which is proprotional to r, the radius of the dome, by the equation $C = 4\pi\varepsilon_0 r$ ε_0 is the permittivity of free space

Charge on the dome, in coulombs, $Q = CV$ C in farad, V in volts (typically 180 kV)

$2\ \text{pF} = 2 \times 10^{-12}\ \text{F}$ $180\ \text{kV} = 180 \times 10^{3}\ \text{V}$

so the charge is $Q = 360 \times 10^{-9} = 0.36 \times 10^{-6}$ coulomb or 0.36 microcoulomb.

An electric current is a flow of charge, and 1 ampere is a flow of 1 coulomb per second $I = Q/t$

If we estimate that the spark from a discharging VdGG dome occurs in 1 millisecond, then the current is $\frac{0.36 \times 10^{-6}}{10^{-3}}$ or 0.36×10^{-3} which is 0.36 mA

0.36 mA is well below the range of lethal currents, so the shock from a VdGG is not life threatening to normal healthy individuals.

The size of the dome limits the energy available which, in turn, limits the current available when the dome discharges. The voltage may be very high, but the current is very small and time limited.

Caution: anyone who has a pacemaker, an implanted hearing device (Cochlear implant), heart condition, or wears hearing aids should take great care to avoid getting shocks from the VdGG. Such people can be affected and devices may possibly be damaged by receiving sparks from the VdGG.

VdGG maintenance

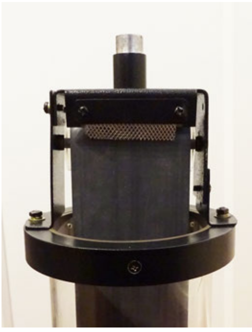
Regular PAT will ensure that the metal case has good earth continuity.
This can also be checked using a good quality multimeter. The resistance between the earth pin in the mains input socket and any point on the metal case should be 0.1 ohms or less. This includes the 4mm socket where the discharge ball fits. Before testing the metal case, connect the test leads together in series to find their resistance - this must be deducted from the readings when testing the earth continuity.

Store the VdGG so that it is protected from damp and dust.
If the generator makes fizzing or hissing sounds when it runs and the sparks are short and weak, then it is likely that dust or damp are the problem.
Dust provides conducting paths from the dome down to the earthed case. Covering the entire generator with a sheet will help to prevent the accumulation of dust, in storage.

DO NOT use spray polishes or surface cleaners as they often contain "anti-static" ingredients!

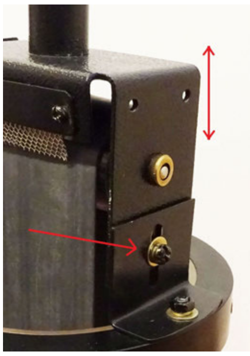
Check that the acrylic cylinder that supports the dome is free from dust. Use a lint free cloth with some isopropyl alcohol to remove any dust, then allow the alcohol to evaporate.

Check the two "combs" - these are rectangular pieces of metal mesh, secured by two screws and a metal plate. The lower one is enclosed and less prone to movement; the upper comb is accessible and might occasionaly require re-alignment. The comb's serrated edge should be straight and parallel with the belt. The gap between the edge and the belt should be approximately 2 mm for both combs. Slacken the two screws to allow the mesh to be adjusted, then re-tighten the screws.



The belt in this version of the VdGG is enclosed by the acrylic cylinder and therefore is less prone to accumulation of dust on the belt.

The belt should run in the centre of the two rollers, without touching or rubbing against the metal roller cage. To check this, remove the dome and connect a long 4 mm plug lead from the socket in the base to the 4mm socket in the top of the roller cage - this takes any charge to earth.



Run the generator and observe the belt's alignment.
To adjust the belt, stop the generator.
Slacken the screw in the elongated hole in the side of the cage.
Tilt the movable part of the cage slightly, tighten the screw,
then run the generator again to check the alignment.

After long use the belt may become stretched and need to be replaced.

Store the VdGG in a warm, dry environment to reduce the effects of dampness. Cover it with a dry sheet
If you suspect the generator is damp, use a hair drier on a low heat to dry the whole apparatus.

The dome
Remove the dome, by pulling it upwards. Check the whole outer surface for scratches and any roughness, also check the inner rim of the dome. Try to remove scratches by polishing - it is aluminium, so a metal polish will probably remove most scratches.
Only use fine sandpaper if the roughness is significant, then polish the surface smooth.
Any irregularity can cause leakage of the charge, limiting the maximum voltage achievable.

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