

Van de Graaff generator

The Van de Graaff generator is a classroom classic with a surprising heritage in cutting-edge particle physics. As well as making your hair stand on end, these machines were used to accelerate particles through millions of volts.

Apparatus

- 1 × Van de Graaff generator
- 1 × electrically-insulating stool
- Some confetti, or aluminium foil, or foil cake trays

The demonstration

This demonstration involves high voltages, and so it should never be done by anyone with a pacemaker or other internal electrical device, or who thinks they might be pregnant.

The first part of this demo requires a volunteer from the audience. It works best on someone with long, light-coloured hair free from ties and styling products: light hair is often thinner, which means it will stand up more easily, and is also easier to see. Don't pick on an individual (they might be pregnant, or just shy!), but if you could encourage someone fitting that description that gives you the best chance of success.

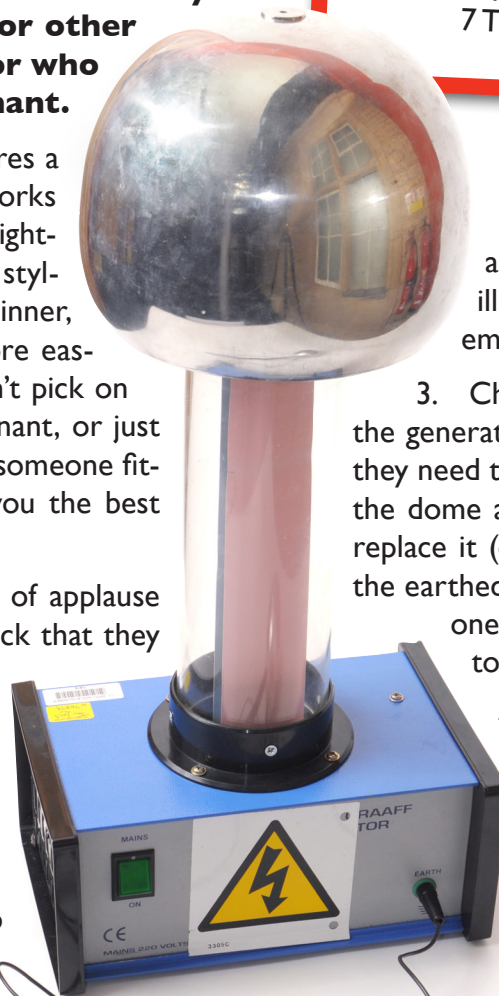
1. Give your volunteer a round of applause and find out their name. Check that they aren't wearing any metal jewelry etc, and ask that they remove it if so. Put it safely to one side.
2. Get the volunteer to stand on an electrically-insulating stool. Place one hand on top of the generator dome, and get them to hold out their other hand flat. In this, place some confetti, pieces of aluminium foil, or cake tins. If you have a suit-

Vital statistics

breakdown voltage of air:
30,000 V/cm

highest-voltage Van de Graaff:
25.5 MV

length of spark from a Van de Graaff LHC:
 $7 \text{ TV} \div 30 \text{ kV/cm} = \mathbf{2300 \text{ km}}$



able light, dim the main lights and illuminate their head from behind to emphasise the forthcoming hairdo.

3. Check they're feeling OK, turn on the generator, and stand back. The only thing they need to do is not to take their hand from the dome and, should they do so, not try to replace it (or they'll get a shock!). Make sure the earthed globe is a long way from the main one to avoid shocking the volunteer too.
 4. The objects in their hand will leap out and, by the time that's finished, their hair should be standing up pretty nicely. Get them to shake their head around a bit to encourage this.
 5. Get the volunteer to take their hand off the dome, and jump down with both feet, and give them a round of applause!
- Having shown the amusing effect of high voltage on a person, we can now

explore the limitations of these devices as particle accelerators. The problem is sparks, and we can use the sparks to work out the voltage to which we charged up our hapless volunteer!

1. If you haven't already, dim the lights.
2. Take the grounded sphere and place it near the dome of the Van de Graaff generator. When you get within a few centimetres, a spark should leap across with a crack. Do this a few times from different angles to show the audience.

How it works

The rubber belt inside the Van de Graaff generator runs between two rollers made of different materials, causing electrons to transfer from one roller to the rubber, and from the rubber onto the other roller, by the triboelectric effect. Brushes at the top and bottom provide a source and sink for these charges, and the top brush is electrically connected to the Van de Graaff's dome and so the charge will spread out across the dome.

This accumulated charge would like to distribute itself over as large a volume as possible, and so it will also spread out across anything you connect to the metal dome, including your volunteer. The reason it's important to stand them on something electrically-insulating is that the charge would like even more to spread out over the whole Earth, and connecting them to that will both massively reduce the effect, and also cause an electric shock as the current flows from the Van de Graaff to earth through its unfortunate human intermediary.

When insulated, the build-up of charge on the volunteer causes forces light objects to spread out as far as possible too, causing the confetti or foil to leap from their hand and then causing the individual hairs on their head to stand up. When they jump off the stool, the charge immediately flows to earth and their hair will immediately return to normal.

To work out the voltage of the Van de Graaff generator, and thus the voltage on our volunteer, we can use the length of the sparks in combination with the breakdown voltage of air—the voltage required to cause air to dissociate into ions and become conductive. This voltage is about 30,000 V/cm for dry air (hot, humid or lower-pressure air will tend to spark more easily). Sparks from the Van de Graaff are typically a few centimetres long, giving a voltage between 50,000 and 150,000 V.



A hair-raising experience with a Van de Graaff generator: illumination from behind helps emphasise the hairdo.

Their propensity to generate sparks is the fundamental limitation of Van de Graaff accelerators, or indeed any accelerator design based on a large, static voltage. Those used for research managed to get up to over 20 MV by clever use of insulating materials, right down to careful choice of the gas in which the generator sits to minimise the chance of sparks. A Van de Graaff can thus be used to accelerate particles up to reasonably high energies: moving an electron through 1 V gains it an energy of 1 eV, so energies of over 20 MeV are achievable by this method (and more if accelerating nuclei with greater than a single electron charge).

However, modern particle physics has gone some way beyond this: the Large Hadron Collider will ultimately use beams which have 7 TeV of energy each: equivalent to accelerating a proton through 7,000,000,000,000 V. If we divide that by the breakdown voltage of air, we can work out the length of a spark we might get from an LHC employing a single, giant Van de Graaff generator to accelerate its particles. We get 2,300 km: easily enough to stretch, for example, from Switzerland to anywhere in the UK.