Electrostatic Accelerators

Joint ICTP-IAEA Workshop on Accelerator Technologies, Basic Instruments and Analytical Techniques
21 – 29 October 2019
Lowry Conradie
Overview of the lecture

1. Charging system to double or triple the voltage
2. Cockcroft-Walton accelerator
3. Van de Graaff accelerator
4. Tandem accelerator
5. Dinamatron / tandemron accelerator
6. Upgrade and maintenance at iThemba LABS electrostatic accelerators
Basic principle of an electrostatic accelerator

The principle of a electrostatic accelerator is shown in the figure below. The voltage from a high voltage generator is connected to the accelerating tube, and the particles are accelerated in one step through the tube, which is constructed as a long drift tube with a number of electrodes along the axis giving a rather uniform field distribution for acceleration.
Basic principle of an electrostatic accelerator

Electrostatic accelerators work by accelerating charged particles through a constant potential difference. If a particle has a charge $q$ and mass $m$ and move through a potential difference of $V$ then it will gain a kinetic energy, $E_{Kinetic}$, of:

$$E_{Kinetic} = \frac{mv^2}{2} = qV$$
Cascade generator (Voltage doubler)

- Basis: Greinacher circuit
High voltage multiplier cascade generator

- Basis: Greinacher circuit

- Cockroft, Walton 1937: 700 kV Nobel Prize 1951: first to show that one element (lithium) could be artificially transformed or transmuted into another.
High voltage multiplier, cascade generator

- Cockroft-Walton-Accelerator

- stationary: $U = 2nU_0$
- under load:
  - mean voltage drop $\Delta U$
  - ripple $\delta U$

$$U_{total} = 2nU_0 - \Delta U \pm \delta U = 2nU_0 - \frac{I}{fC} \left( \frac{2}{3}n^3 + \frac{1}{4}n^2 + \frac{1}{12}n \right) \pm \frac{I}{fC} \cdot \frac{n(n+1)}{2}$$

For small $\Delta U$ and small $\delta U$:
- high frequency of the alternating voltage
- high capacity $C$
- small number of steps $n$

- Typical values:
  - $f = 0.5 - 10$ kHz
  - $C = 1 - 10$ nF
  - $n = 3 - 5$

$U = U_0 \sin(2\pi ft)$
High voltage multiplier cascade generator

- Cockroft-Walton-Accelerator

- High voltage terminal: particle source
- Rotating rods made of insulating material for drive and control
- Optical fibers for data transmission

\[ U = U_0 \sin(2\pi f t) \]
Cacade generator

- Cockcroft-Walton at PSI, 870 kV
- Injector accelerator for injecting beam into the injector 2 cyclotron at PSI
Estimate of maximum voltage on high voltage terminal

Corona breakdown

Partial breakdown of the air occurs as a corona discharge on high voltage conductors at points with the highest electrical stress. Conductors that have sharp points, or balls with small radii, are prone to causing dielectric breakdown, because the field strength around points is higher than that around a flat surface. High-voltage apparatus is designed with rounded curves and grading rings to avoid concentrated fields that can cause breakdown of the high voltage.

• Electric field strength on the surface of a sphere
  = Voltage / Radius

• In dry air: breakdown at 3 kV / mm
  → at radius = 1 m: Umax = 3 MV

• In practice: only about one third of this value reached

• Solution: Pressure tank with insulating gas
Accelerator - Tube

- Good vacuum in the accelerator tube to prevent flashovers due to residual gas (also minimizes particle losses)
- Insulating rings with intermediate electrodes
- Intermediate electrodes connected via resistor chain to achieve a uniform voltage drop along the tube
Ion implanters (mostly of the Cockcroft Walton type)

Ion implantation is a low-temperature process by which ions of one element are accelerated into a solid target, thereby changing the physical, chemical, or electrical properties of the target. Ion implantation is used in semiconductor device fabrication and in metal finishing, as well as in materials science research.
Part of the charging system top and the accelerator tube of ion implanter at iThemba LABS
Van de Graaff Accelerator

- Charge is sprayed on an insulating belt (field emission)
- Circulating belt:
  - transports charge to the high voltage terminal
  - drives generator in the terminal, so that energy is available for source
- Pressure tank for protection against flashovers
- Accelerating tube
- Charge collector
- Pulley, generator
- Charging of belt
- Belt drive

Joint ICTP-IAEA Workshop 21 – 29 October 2019 Trieste Italy
Controlling the maximum voltage on the high voltage terminal
Signals from two capacitive probes 180 degrees apart monitoring the high voltage terminal

CPO signals

Mechanical movement in the column and field changes due to electrostatic discharges
Inert gasses as insulating gas for electrostatic accelerators

The dielectric strength of the gas/mixture
Depends mainly on its capability to reduce the density of electrons that are generated when it is subjected to an electric field. For this purpose, the gas must be electronegative to reduce the number of electrons by attachment. The gas must be able to slow down electrons to capture them efficiently at lower energies and thus avoid the generation of other electrons by impact ionization.

Sulfur hexafluoride
(SF$_6$) is an inorganic, colourless, odourless, non-flammable, non-toxic and an excellent electrical insulator. The high dielectric strength is a result of the gas's high electronegativity and density. Exposure to an arc chemically breaks down SF$_6$ though most of the decomposition products tend to quickly re-form SF$_6$, a process termed "self-healing".

Dielectric field strength N$_2$ and CO$_2$ relative to SF$_6$

<table>
<thead>
<tr>
<th>Gas</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>0.32 – 0.37</td>
</tr>
<tr>
<td>N$_2$</td>
<td>0.34 – 0.43</td>
</tr>
</tbody>
</table>

In practice mixtures of N$_2$-O$_2$ under lightning impulse voltages exhibit better performance (dielectric strength) than those of N$_2$ or CO$_2$ on their own
Pressure tank and inert gas

• Typical gas mixtures

<table>
<thead>
<tr>
<th>SF₆</th>
<th>N₂</th>
<th>CO₂</th>
<th>Pressure (atm)</th>
<th>Uₘₐₓ (MV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 %</td>
<td>20 %</td>
<td></td>
<td>14</td>
<td>9.6</td>
</tr>
<tr>
<td>60 %</td>
<td>40 %</td>
<td></td>
<td>6</td>
<td>9.7</td>
</tr>
<tr>
<td>100 %</td>
<td></td>
<td></td>
<td>7</td>
<td>13.0</td>
</tr>
</tbody>
</table>

• Good dielectric gas: SF₆ has withstood voltages of 40 MV/m at 8 bar
• Very important to note: gas purity and dryness
• Example: moisture in SF₆
  o Reduction of the dielectric strength
  o Formation of toxic gases
Toxicity of some by-products resulting from the decomposition of SF6

<table>
<thead>
<tr>
<th>Gas</th>
<th>Tolerated Quantity (mg/m³)</th>
<th>Degree of Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF₄</td>
<td>0.1</td>
<td>Moderately toxic</td>
</tr>
<tr>
<td>SOF₄</td>
<td>2.5</td>
<td>Little toxic</td>
</tr>
<tr>
<td>SOF₂</td>
<td>2.5</td>
<td>Little toxic</td>
</tr>
<tr>
<td>SO₂F₂</td>
<td>5</td>
<td>Moderately toxic</td>
</tr>
<tr>
<td>SO₂</td>
<td>2</td>
<td>Moderately toxic</td>
</tr>
<tr>
<td>S₂F₁₀</td>
<td>0.025</td>
<td>Very toxic</td>
</tr>
<tr>
<td>SiF₄</td>
<td>2.5</td>
<td>Little toxic</td>
</tr>
<tr>
<td>HF</td>
<td>3</td>
<td>Moderately toxic</td>
</tr>
</tbody>
</table>
Van-de-Graaff Accelerator at HZB

Equipotential rings, internally connected by resistance chain, for uniform voltage drop over length.
Van de Graaff accelerator at HZB

Silver: "Dome", comes over the terminal to avoid spray discharges and flashovers
Red: pressure tank, comes over the entire accelerator

Pressure tank is pumped out and then filled with 5 bar SF$_6$
- U$_{\text{max}}$ = 6 MV
- $\delta V / V \leq 10^{-4}$
Terminal of Helmholtz Zentrum Berlin

• Terminal of the HZB Van-de-Graaff
• Permanent magnet 5 GHz ECR ion source (BECRIS)
• Gas bottles for rapid change of the ion type
• Wien filter for the preselection of the charge state
• Buncher and focusing elements
Different sections of the 6 MV CN Van de Graaff accelerator at iThemba LABS
Tandem Accelerator

• Positive voltage at the terminal (here: band generator)
• Negative ions are accelerated from source to terminal
• Charge exchange by stripping in the terminal
• Second acceleration from the terminal to ground
High voltage generated by belt generator or by dynamitron principle (Van-de-Graaff, Tandetron)

Require lower terminal voltage for the same energy obtained with a Van de Graaff:

\[ E_{\text{kin}} = eU + qU = (e+q)U \]

- For 4 MeV Protons: require 2 MV terminal voltage
- 12 MeV Cl: require 4 MV terminal voltage, for stripping in the terminal to 2+

only for elements that also form neg. ions

Thus no noble gasses except He

The ion source is at ground potential: easier access for maintenance (BIG ADVANTAGE)

Stripping in the terminal via foils have to be reloaded:

- higher charge states after the stripper possible
- limited life of the foils limited, thus lower beam current longer life time of foils

Stripping in terminal with gas:

- Does get lower charge states than stripping with foils and also lower current
- Can run for a number of years before the stripping gas bottle in the terminal has to be filled up
- Pelletron chain produce much less fluctuation in terminal potential because the charge is deposited on the chain of pellets by induction, a process insensitive to surface irregularities, which are a common problem with belts.
- Pelletrons run dust free and need to be replaced once every 5-7 years. Comparison with the a belt charging system it is a much cleaner environment. Pelletron chain replacement is a much faster process than changing a belt.
Voltage stability with a pelletron charging system

• The high frequency ripples are due to the arrival of the individual charges on the pellets,

• The slower fluctuations are due to non-uniformities in the charging and discharging pulleys.

• The typical time-dependent voltage fluctuations on the terminal observed for a chain charging system are much less than 0.1%, and can, in a well adjusted system, approach 0.01% or better.
- Further development of the cascade generator
- Semicircular RF electrodes
- Rectifier diodes connected via semicircular coronal rings
- between HF electrodes:
  strong RF field with some 100 kHz
- → Waiver of smoothing capacitors possible
- In corona rings, HF current is induced
- → Rectifier chain capacitively coupled to RF electrodes
- $\delta V/V \leq 10^{-3}$
- 3 MV tandemron can deliver 500 micro ampere of beam current
- Manufacturer:
  - Radiation Dynamics Inc
  - HVEE
Dynamitron also known as Tandetron
Tandetron at HZB

• 2 MV Tandetron from the company HVEE
• Used from 2011 as injector for the K130 cyclotron used for eye therapy
Tandetron Accelerator at HZB

- Tandetron HZB, $U = 2$ MV
- Voltage generation via Dynamitron principle
- 2 ion sources for improved reliability
Tandetron 6 MV accelerator from HVEE

On the market 6 MV tandetron and they have a design for 8 MV tandetron
iThemba LABS 6 MV EN Tandem accelerator used for AMS
Tandem injection side
Injection system for 6 MV EN tandem accelerator of iThemba LABS
Injection beam optics from AMS ion source to middle of tandem

Bouncer acceleration gaps

Q-snout

einzel lenses

90 degree electrostatic analyser $r = 300$ mm

Energy/charge state ratio = 90 keV

90 degree bending magnet $r = 600$ mm

Maximum mass energy product $= 15.6$ MeV amu

einzel lenses

Acceleration tube
Refurbishment of the 6 MV EN Tandem Accelerator
Landscape Erosion

River Ecology

Applications of AMS

Burial Dating

Dating of Archaeological Artefacts

Climate Research
Control room 6 MV Van de Graaff 2003 iThemba LABS
Layout – HV Terminal

Joint ICTP-IAEA Workshop 21 – 29 October 2019 Trieste Italy
Beam Envelope in Terminal Calculated with the Program IGUN
Beam Profile in the Van De Graaff - 2 MeV Protons

BEAM PROFILE IN THE VAN DE GRAAFF -- 2 MeV p+

5.285 keV p+ --> 10 keV --> 2 MeV

Einzel1=4.705; Buncher=2.6; Acc=-4.715; Einzel2=4.651 kV
24 Digital meters installed in the terminal of the 6 MV CN Van De Graaff (survive 16 bar pressure and all the sparks for 6 Years)
Pressure vessel for pressure testing components in the high voltage terminal
Larger pressure vessel to pressure test the complete assembled high voltage terminal of the Van de Graaff accelerator
Van de Graaff terminal voltage stabilizing unit
Voltage stabilization by controlling the corona current
Displaying information of the 2 capacity pickups, generating volt meter and current difference on the analysing slit jaws
New energy stabilization slits system
Energy measurement at the Van de Graaff

Beam energy determination for the Van de Graaff accelerator

NMR frequency

- 15.998 MHz

Hall-probe signal

- 27.967 mV

Magnetic field

- 3.7574 kG

- 3.7517 kG

Calculated beam energy

- 3.008 MeV

- 2.999 MeV
Control Room 6MV CN Van de Graaff 2014
iThemba LABS
3 MV Tandetron at iThemba LABS
High energy beam line of the tandetron accelerator
What to take into account to ensure a well maintained accelerator facility

- What is the maintenance strategy of your installation? (predictive, corrective, emergency, regulatory maintenance)
- How to explain to the management that the consolidated cost of equipment including maintenance cost and running cost should be considered when designing and purchasing new equipment?
- Using in-house resources or an external company to do the maintenance
- How to ensure equipment is easy to maintain? needing little time to be fixed, replaced, etc.?
- How to handle large system maintenance as in the case of a cooling plant refurbishment when the facility is aging?
- Maintenance of software (controls, equipment firmware, etc)
- Maintenance impact on the planning of the shutdown periods (what strategy?)
- Maintenance strategy and prioritization the resources in a large accelerator complex
Safety interlock system for personnel and equipment safety
# Parts list of Van de Graaff accelerator

## Van de Graaff Parts List

### Terminal

<table>
<thead>
<tr>
<th>Item</th>
<th>Image</th>
<th>Part No.</th>
<th>Company</th>
<th>URL</th>
<th>Dimensions</th>
<th>In use</th>
<th>Spares</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duoplasmatron source</td>
<td><img src="#" alt="Image" /></td>
<td>350</td>
<td>Iomex</td>
<td><a href="http://www.highvoltageeng.com/">http://www.highvoltageeng.com/</a></td>
<td>152mm Dia 192</td>
<td>1</td>
<td>1</td>
<td>R4032</td>
</tr>
<tr>
<td>Gauze Filament 80 mesh .003</td>
<td><img src="#" alt="Image" /></td>
<td>G350A0302</td>
<td>High Voltage Engineering</td>
<td><a href="http://www.highvoltageeng.com/">http://www.highvoltageeng.com/</a></td>
<td>2</td>
<td>8</td>
<td></td>
<td>$598.00</td>
</tr>
<tr>
<td>0.25uF Mica Capacitor 25KVDC</td>
<td><img src="#" alt="Image" /></td>
<td>MD2BY254K</td>
<td>SorApower Inc</td>
<td><a href="http://www.sorapower.com/">http://www.sorapower.com/</a></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Einzel 2 power supply</td>
<td><img src="#" alt="Image" /></td>
<td>M2</td>
<td>Technipower</td>
<td><a href="http://www.inotek.com/catalog/technipower1pc.html">http://www.inotek.com/catalog/technipower1pc.html</a></td>
<td>5</td>
<td>2</td>
<td></td>
<td>$248.00</td>
</tr>
<tr>
<td>Variac M2 Single phase 120V 400Hz 2.4A</td>
<td><img src="#" alt="Image" /></td>
<td>M5</td>
<td>Technipower</td>
<td><a href="http://www.inotek.com/catalog/technipower1pc.html">http://www.inotek.com/catalog/technipower1pc.html</a></td>
<td>2</td>
<td>1</td>
<td></td>
<td>$266.00</td>
</tr>
<tr>
<td>Gas bottles</td>
<td><img src="#" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Voltage Resistor 100Meg 2%</td>
<td><img src="#" alt="Image" /></td>
<td>100.4-100M-GT-A</td>
<td>Nicrom Electronics</td>
<td><a href="http://www.nicrom-electronic.com/">http://www.nicrom-electronic.com/</a></td>
<td>100</td>
<td>100</td>
<td></td>
<td>R50</td>
</tr>
<tr>
<td>Dome</td>
<td><img src="#" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General purpose relay</td>
<td><img src="#" alt="Image" /></td>
<td>HFW5A1201S501</td>
<td>TE Connectivity</td>
<td><a href="http://www.te.com">http://www.te.com</a></td>
<td>2</td>
<td>2</td>
<td></td>
<td>$138.23</td>
</tr>
<tr>
<td>Thermo electric leak</td>
<td><img src="#" alt="Image" /></td>
<td></td>
<td>Potentials Inc</td>
<td><a href="http://www.potentialsinc.com/">http://www.potentialsinc.com/</a></td>
<td>5</td>
<td></td>
<td></td>
<td>$831.60</td>
</tr>
<tr>
<td>Current Injection Transformer</td>
<td><img src="#" alt="Image" /></td>
<td>220V/230V to 0.5V @ 75A</td>
<td>Eloff Transformers</td>
<td><a href="http://www.elofftransformers.co.za/">http://www.elofftransformers.co.za/</a></td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>R552.90</td>
</tr>
</tbody>
</table>
The ELOG Home Page

Home of the Electronic Logbook package by Stefan Ritt

Current version is: 3.1.2

What is ELOG?

**ELOG** is part of a family of applications known as *weblogs*. Their general purpose is:

1. To make it easy for people to put information online in a chronological fashion, in the form of short, time-stamped text messages ("entries") with optional HTML markup for presentation, and optional file attachments (images, archives, etc.)

2. To make it easy for other people to access this information through a Web interface, browse entries, search, download files, and optionally add, update, delete or comment on entries.

**ELOG** is a remarkable implementation of a *weblog* in at least two respects:

- Its simplicity of use: you don't need to be a seasoned server operator and/or an experimented database administrator to run **ELOG**; one executable file (under Unix or Windows), a simple configuration text file, and it works. No Web server or relational database required. It is also easy to translate the interface to the appropriate language for your users.

- Its versatility: through its single configuration file, **ELOG** can be made to display an infinity of variants of the *weblog* concept. There are options for what to display, how to display it, what commands are available and to whom, access control, etc. Moreover, a single server can host several *weblogs*, and each *weblog* can be totally different from the rest.
• Web access
  • Reachable from any computer with Web Browser
  • Monolithic C(++) program
    • Faster than interpreted languages
    • Needs less memory, runs nicely on Raspberry PI
    • Does not depend on Web servers
    • No dependency of external libraries (except SSL and Kerberos)
    • Simple to compile and install
  • Recent extensions in JavaScript
• “Designed by user”
  • Only contains features that are needed
  • (Most) needed features are contained
• Configurable
  • Can be electronic logbook, discussion forum, bug tracker, ...
  • Huge number of configuration options
  • Some will be covered in this seminar
# Beam statistics of the tandetron accelerator

## Tandetron Accelerator

### STATISTICS

<table>
<thead>
<tr>
<th>STATISTICS</th>
<th>HOURS</th>
<th>Percentage of Calendar time</th>
<th>Financial year</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEAM SUPPLIED</td>
<td>607.06</td>
<td>84.3</td>
<td>75.5</td>
</tr>
<tr>
<td>Beam available</td>
<td>161.28</td>
<td>22.4</td>
<td>27.5</td>
</tr>
<tr>
<td>Beam on target</td>
<td>445.78</td>
<td>61.9</td>
<td>48.0</td>
</tr>
<tr>
<td>to experimental physics</td>
<td>607.06</td>
<td>84.3</td>
<td>75.5</td>
</tr>
<tr>
<td>Environment physics</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Material science</td>
<td>286.56</td>
<td>39.8</td>
<td>39.4</td>
</tr>
<tr>
<td>Nuclear microprobe</td>
<td>320.50</td>
<td>44.5</td>
<td>36.0</td>
</tr>
<tr>
<td>Macro pixe</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Nuclear physics</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Experiment Development</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>NO BEAM SUPPLIED</td>
<td>112.89</td>
<td>15.7</td>
<td>24.5</td>
</tr>
<tr>
<td>Beam development</td>
<td>43.00</td>
<td>6.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Energy changes</td>
<td>23.97</td>
<td>3.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Holidays</td>
<td>0.00</td>
<td>0.0</td>
<td>4.9</td>
</tr>
<tr>
<td>Interruptions</td>
<td>35.50</td>
<td>4.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Maintenance</td>
<td>5.50</td>
<td>0.8</td>
<td>6.7</td>
</tr>
<tr>
<td>Retuning</td>
<td>4.92</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Power fail</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>ENERGY CHANGES</td>
<td></td>
<td>Various</td>
<td>Accumulated</td>
</tr>
<tr>
<td>Number</td>
<td>66</td>
<td>104.0</td>
<td>13</td>
</tr>
<tr>
<td>Average time (hours)</td>
<td>0.4</td>
<td>0.9</td>
<td>5</td>
</tr>
</tbody>
</table>

---

Joint ICTP-IAEA Workshop 21 – 29 October 2019 Trieste Italy
Very happy staff after the first beam from the new Tandetron accelerator (2016)
Thank You