FN Tandem Van de Graaff Accelerator at Notre Dame

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NSL

History of Accelerators at Notre Dame

Notre Dame has a long history of having a particle accelerator on campus – one of the oldest facilities in the United States.

The first accelerator was hand made in the late 1930's, consisting of a copper sheet hammered into place over a pine wood frame to form the terminal electrode.
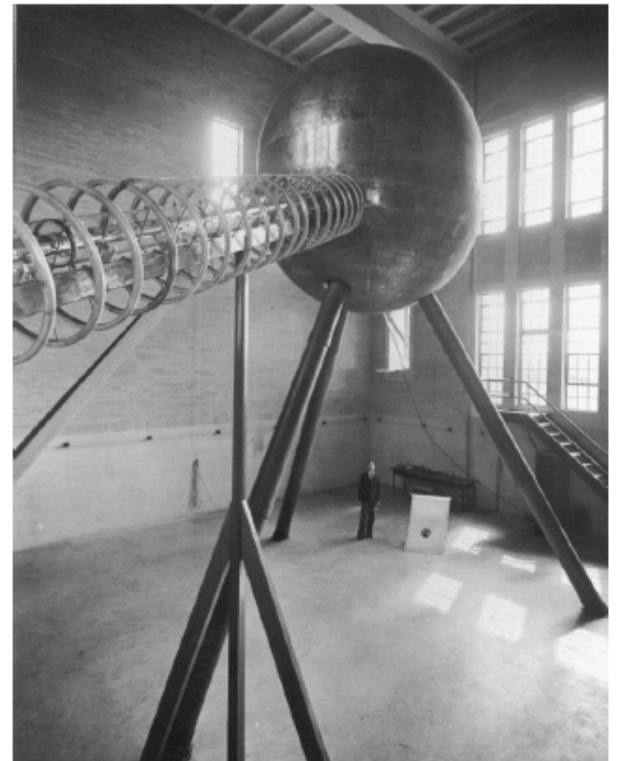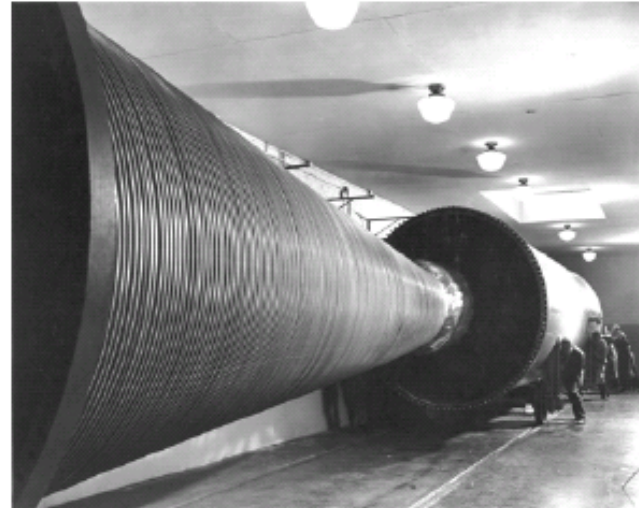
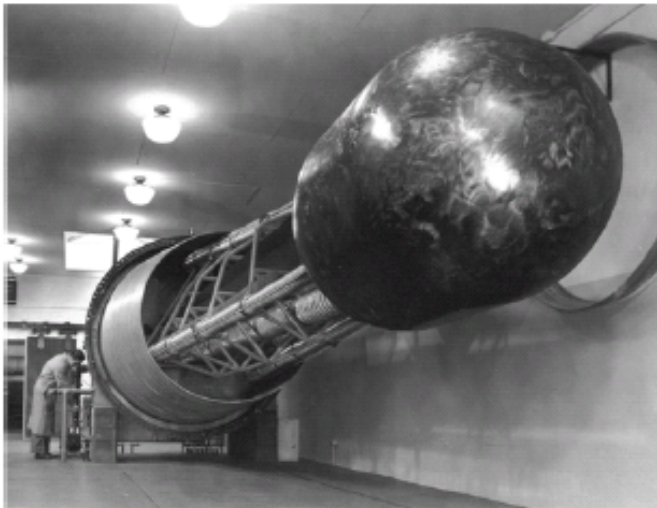# History of Accelerators at Notre Dame

This hand-made accelerator was capable of approximately 2 MV (megaVolts) in air, depending upon the local weather conditions.

Shown here is a "spark", or electrical discharge, along one of the supporting columns when the accelerator was operating at approximately 1.2 MV
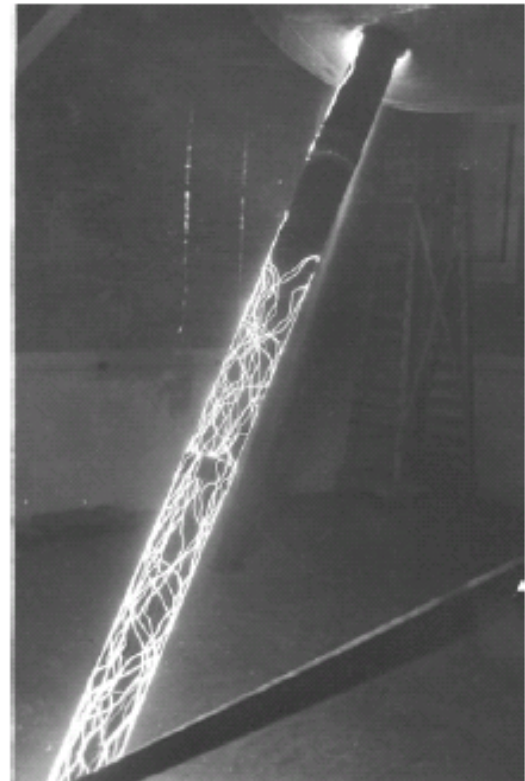
History of Accelerators at Notre Dame

The next accelerator was a "modern" Van de Graaff accelerator, housed in the Lafortune Building, which was the science building during the 1940's.
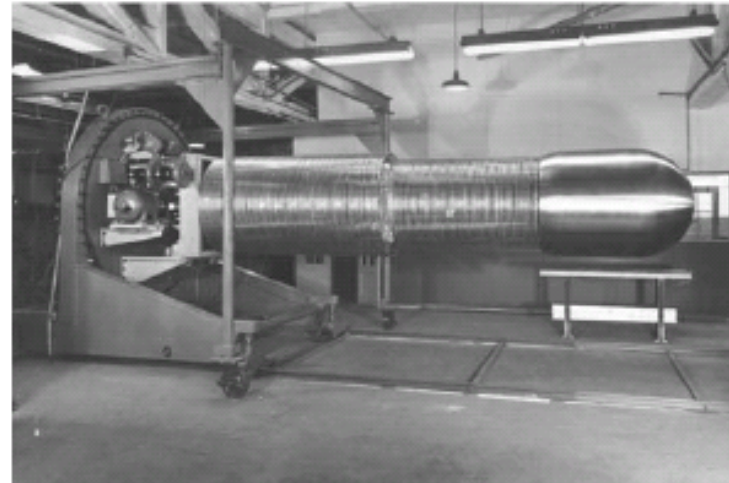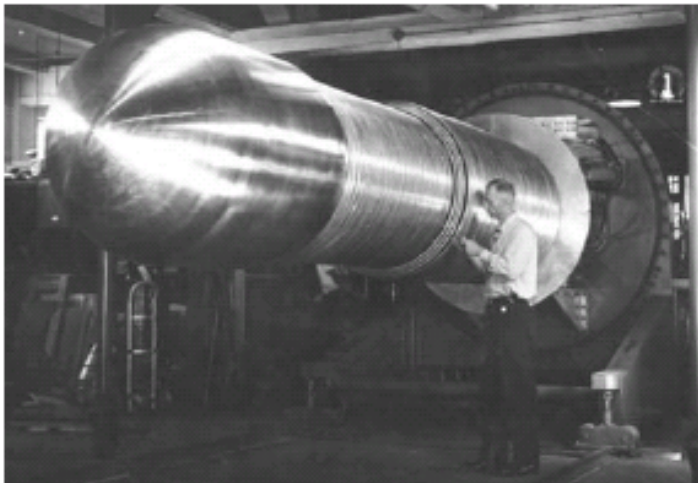
History of Accelerators at Notre Dame

In addition to the research done here at Notre Dame, this machine was also used by the US Government during the Manhattan Project to build the atomic bomb during World War II.

Manhattan Project Researchers traveled to Notre Dame daily from Chicago, irradiating a variety of samples.
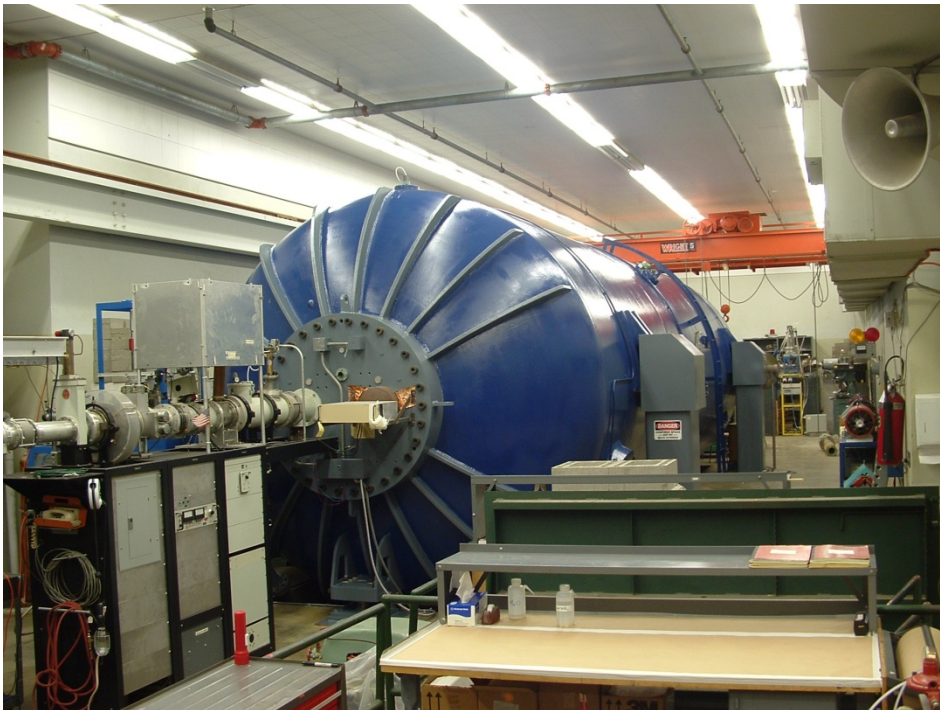
History of Accelerators at Notre Dame

During the 1950's another home-made Van de Graaff type accelerator was built at Notre Dame, and was housed in the present facilities in Nieuwland Science Hall. This machine, capable of about 4 MV, was in service through the late 1980's.

History of Accelerators at Notre Dame

The FN Tandem accelerator was purchased and brought to the facilities in the late 1960's and has been the primary accelerator for the laboratory since that time.

It has been upgraded several times over the years, including new accelerating tubes, new column resistors, and the installation a new charging system known as a pelletron.

History of Accelerators at Notre Dame

The KN (4 MV) and JN (1 MV) accelerators arrived in the 1990's. Each of these accelerators had been de-commissioned at its previous home (each in Canada) before being given to the laboratory and brought here for installation by our students, post-doc, staff, and faculty.

Layout of the Lab
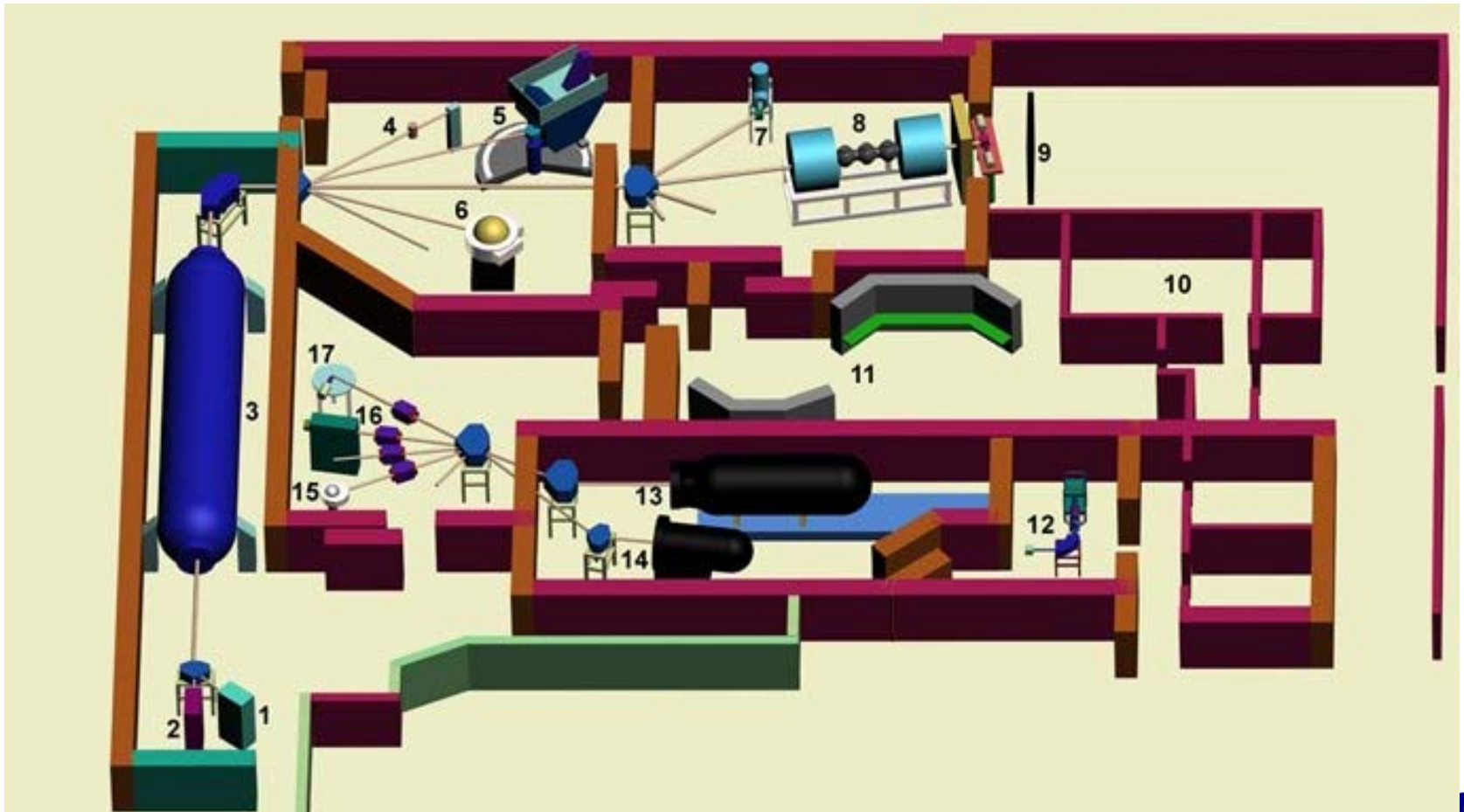
How to Build a Particle Accelerator

- The easiest way is to take advantage of Coulomb's Law.
- Imagine placing a charged particle near a large metal surface charged with the opposite sign.
- Coulomb's Law states that the particle will accelerate towards the metal surface, and that the acceleration depends on the mass of the particle, the charge on the particle, and the strength of the electric field of the metal surface.

$$\vec{F} = Q \cdot \vec{E}$$

$$= m \cdot \vec{a}$$

Charged Particle

Metal surface charged with opposite sign
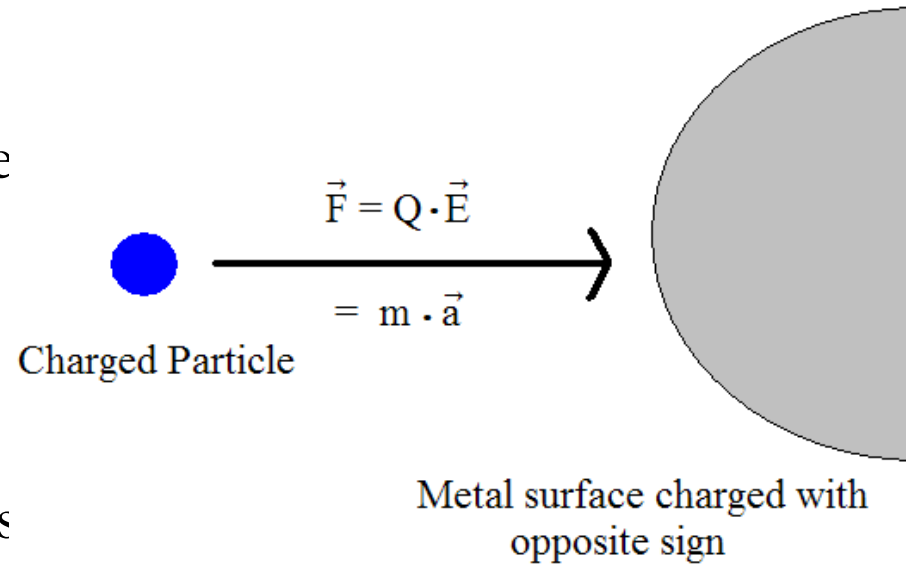
Van de Graaff Generators

A metal sphere is located at one end of an insulating column.

A motor driven belt runs inside the column, and a high voltage power supply mounted in the base sprays charge onto the belt as it passes by.

The charge is removed by sharp Corona needles and uniformly distributes over the surface of the sphere.

Table Top Van de Graaff Accelerator
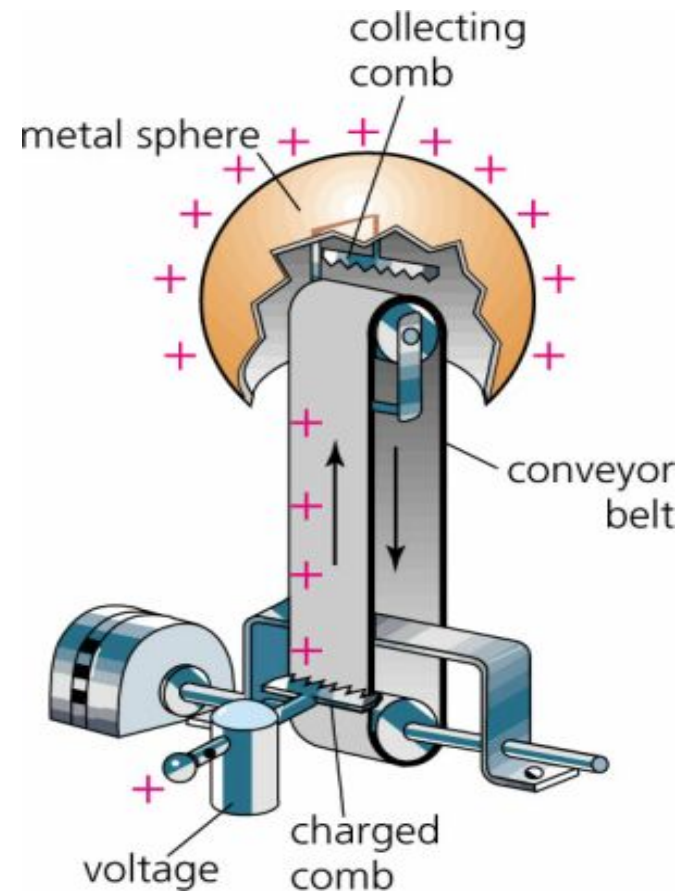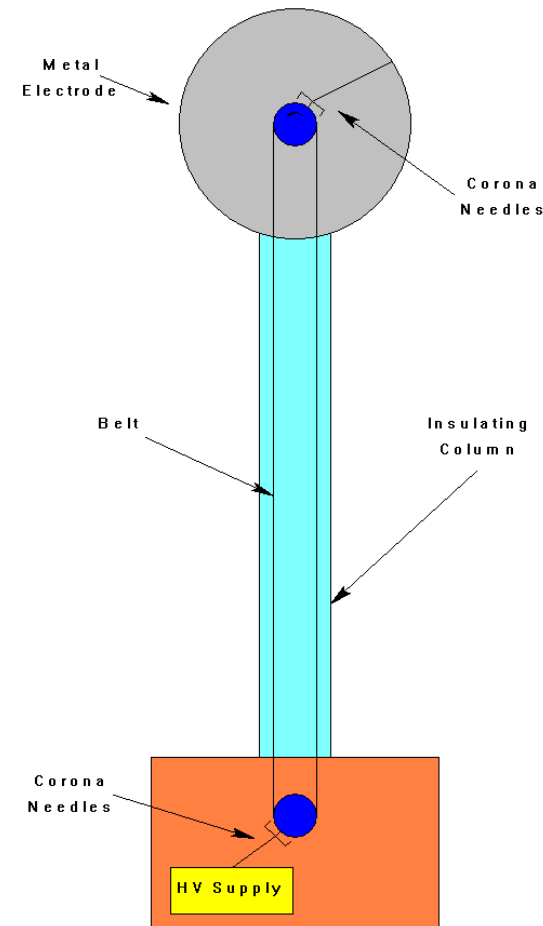
- Problem #1
  - The charged particle accelerates to the "dome", but slams into it – not very useful.

- Problem #2
  - The charged particle collides with atoms in the air on its way to dome, which can cause deflections, interactions, and/or charge exchange.

- Solution?
  - Evacuated beam tube.

Metal Electrode

Corona Needles

Belt

Insulating Column

Corona Needles

HV Supply

Van de Graaff Table Top Accelerator With Beam Line

- An evacuated tube, or beam line, is added to the model, passing entirely through the dome.
- The charged particle can now freely accelerate towards the dome, traveling in vacuum through the beam line.
- However, there are still problems.

Evacuated Beam Tube

Metal Electrode

Corona Needles

Belt

Insulating Column

Corona Needles

HV Supply
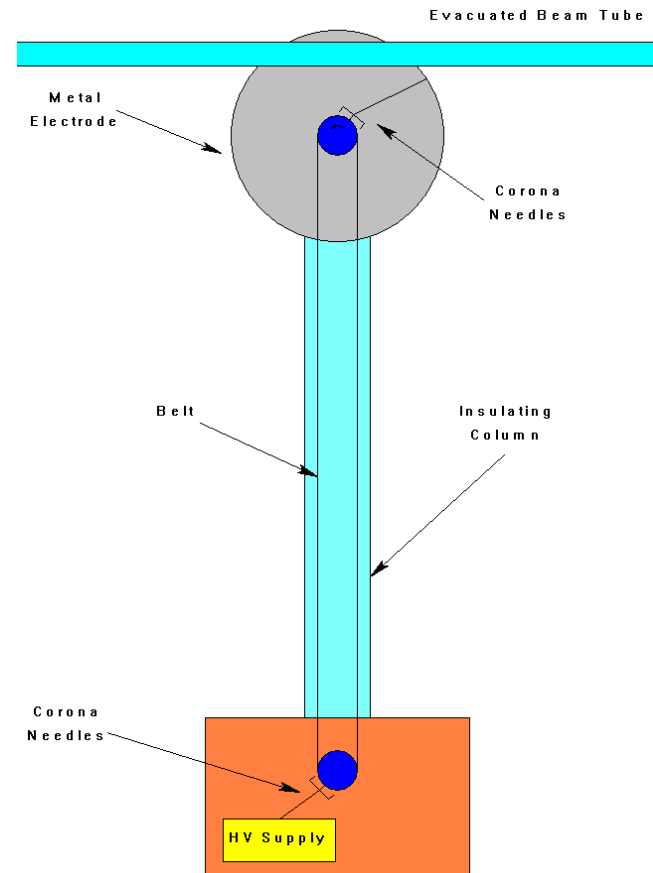
More Problems

- Problem #1
  - Acceleration is non-linear, varying as $1/r^2$ due to the electric field.
  - This means that the field is very strong near the dome, and weak elsewhere.
  - The strong field near the dome can lead to electrical discharging (sparks).
  - And, the charged particle travels a significant distance at fairly low velocity, which makes it very susceptible to deflection by stray fields.
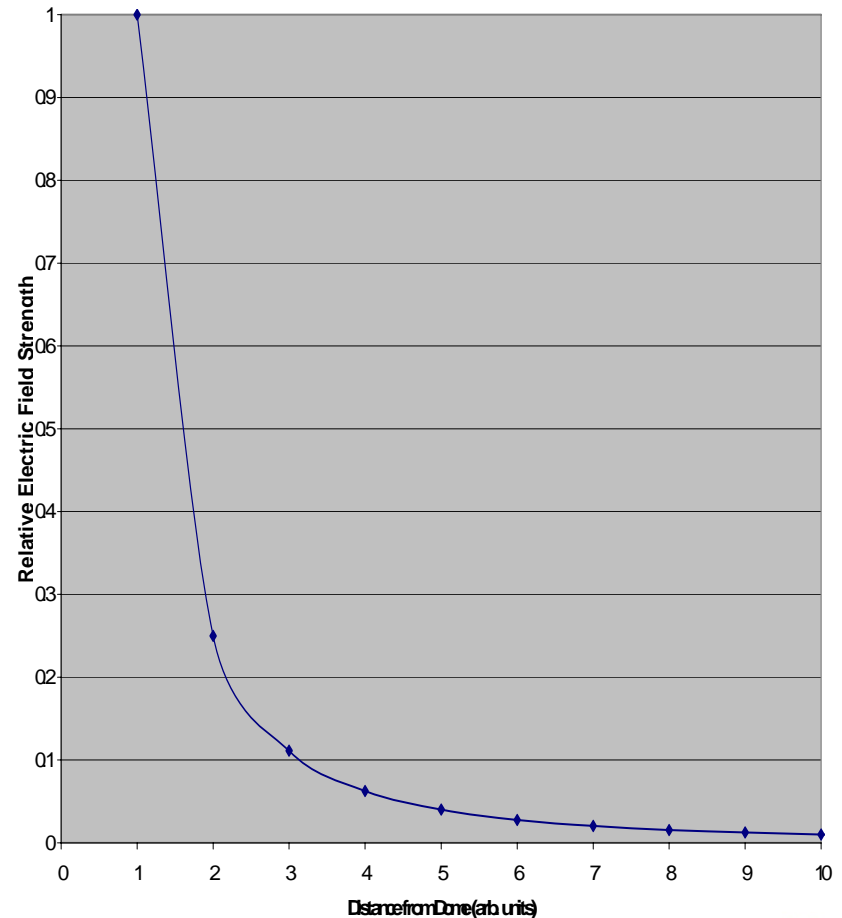
Controlling the Gradient

- The problem of the non-linear acceleration along the tube is solved by building the tube in segments, where glass cylinders are glued to dish-shaped metal electrodes with an aperture in the center.

- Resistors are connected between each metal electrode in the tube, creating a voltage divider circuit.

- Charge continually flows from the dome down to ground through the resistors, and therefore the charging system must continually replenish this charge.

- The voltage increase across each gap is therefore controlled, and is the same across each gap if equal valued resistors are used.

Evenly Spaced
Metal Electrodes

Beam Tube

Resistors
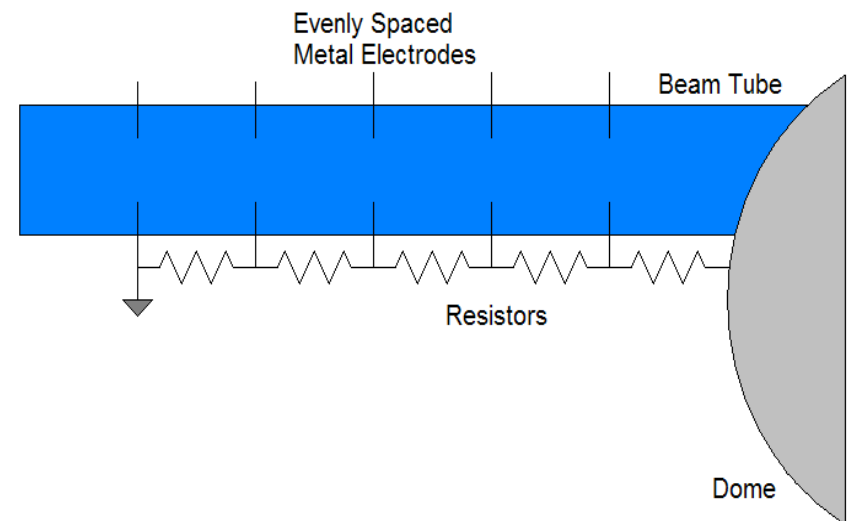
Dome

Uniform Gradient

- In our FN Tandem accelerator, there are about 200 such gaps, and the resistance across each gap is 600 MΩ.

- The total resistance between the dome (also called the terminal) and ground is therefore

$$R_{tot} = 200 \times 600 \text{ M}\Omega$$
$$= 120 \text{ G}\Omega$$

- To reach a voltage of 10 MV on the terminal therefore requires a current of

$$I = 10 \text{ MV} / 120 \text{ G}\Omega$$
$$= 83 \text{ }\mu A$$

- This is a small current by laboratory standards and is easily achieved by any of several methods.

- Remember that this current is flowing from the terminal to ground all the time, so the charging system must continuously replenish this current.
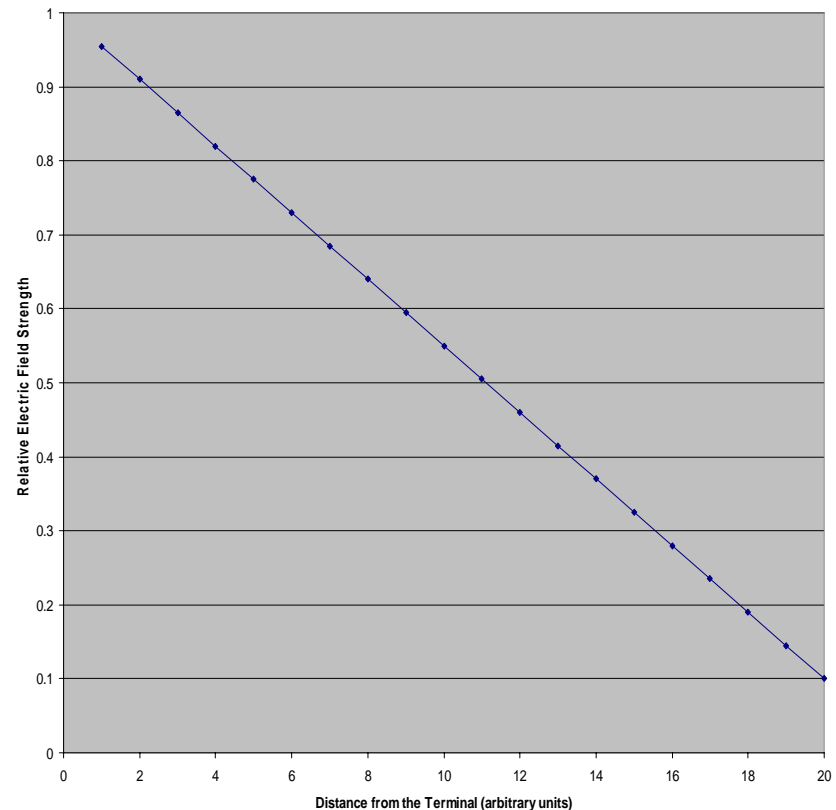
Yet Another Problem

- Problem #2 – If the charged particle accelerates as it moves toward the terminal, then it will decelerate as it exits the terminal region, oscillating in the tube until it comes to rest in the terminal region.

- Simply put, there's no such thing as a free lunch.

- How to solve this problem?
  - Solution is clever, and is the reason that the FN accelerator is known as a Tandem.

Evacuated Beam Tube

Metal Electrode

Corona Needles

Belt

Insulating Column

Corona Needles

HV Supply
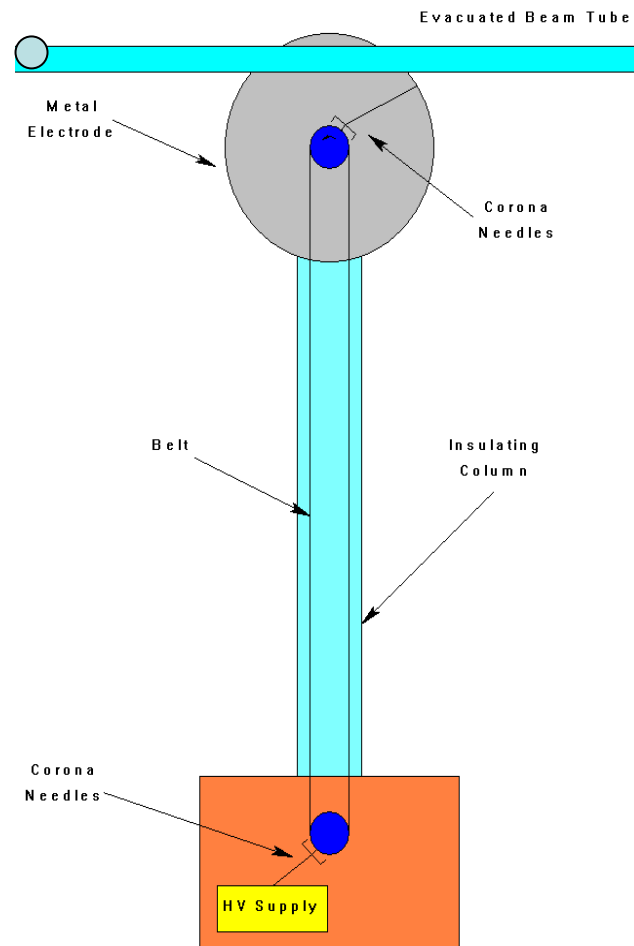
How to get the beam through the Tandem accelerator

- In the case of a Tandem accelerator, such as our model FN, the terminal is charged to a **positive** potential.
- This means that a **negatively** charged beam must be provided by some type of external ion source.
- **Negatively** charged beams are difficult to produce, because they require the addition of electrons to the originally neutral atom to produce the negative ion. However, this can be done with any of several ion source types (more about this later).
- The advantage of doing things this way is that one can get "two accelerations for the price of one".
- **How?**

Making beams for the Tandem

Negatively charged beams for use in the Tandem are produced by ion sources outside the accelerator.

SNICS II Schematic Diagram

Einzel Lens

Lithium Charge Exchange

Duoplasmatron

Helium Ion Souce (HIS)
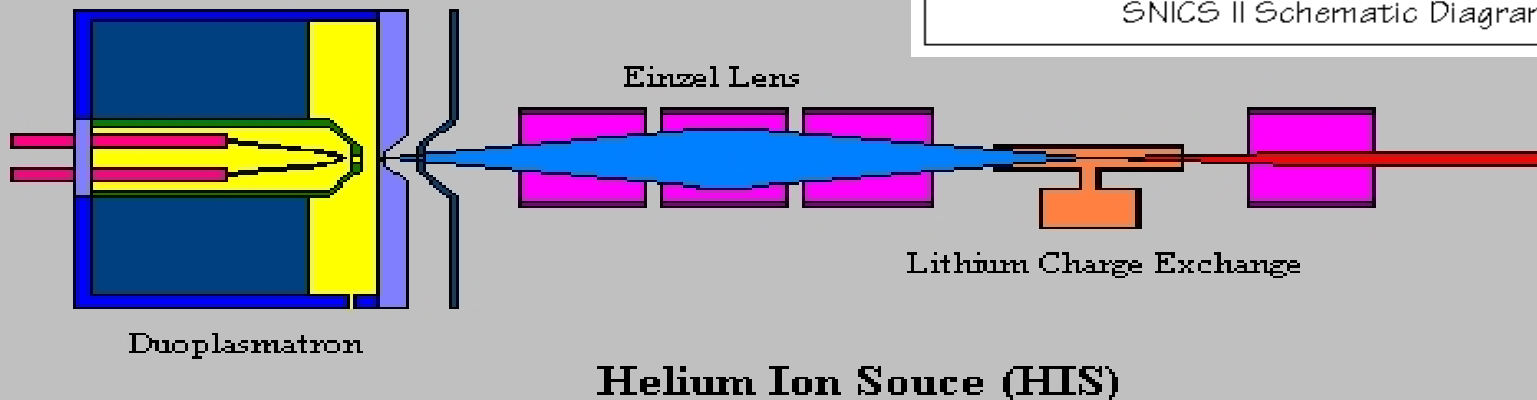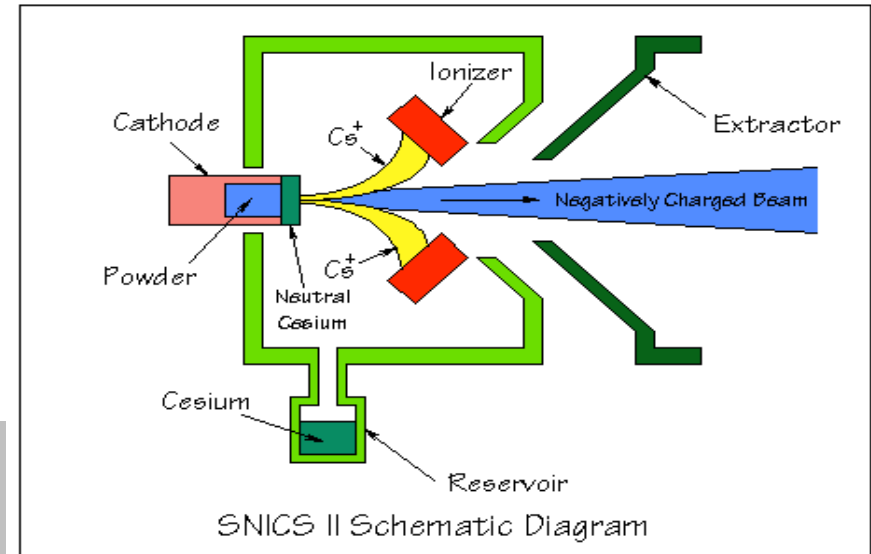
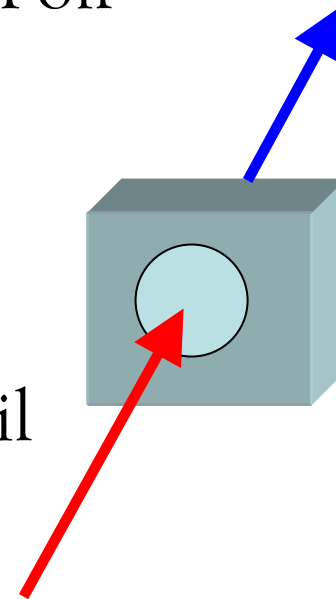# The Stripper Foil

- A thin carbon foil is placed in the beam tube at the center of the terminal. As the negatively charged beam strikes the foil (at fairly high energy), electrons are stripped from the ions, leaving them positively charged.

Positively Charged Beam Exits the Stripper Foil

$3 \ \mu g/cm^2$ Carbon Stripper Foil

Negatively Charged Beam Enters the Stripper Foil

A Basic Diagram of the FN Tandem
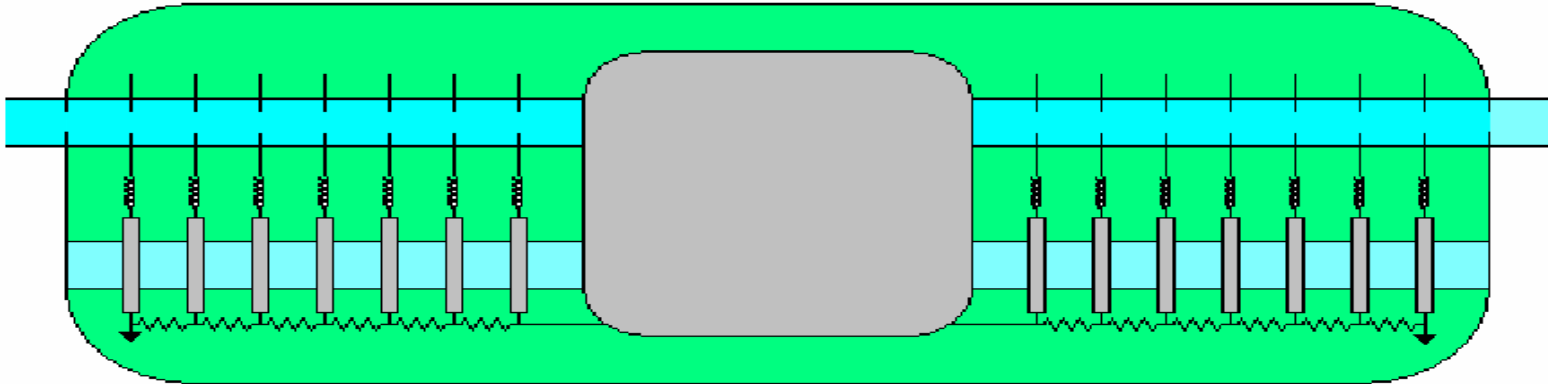
- The terminal is supported by a structure known as the column, which is a sandwich of glass blocks and metal planes. The column is held in place by compression supplied by a huge spring. The beam tubes are mounted along the side of the column.

- The resistors are actually mounted on the column instead of along the tube, and each plane of the column is connected to the corresponding plane in the tube by a metal spring.

- The entire accelerator is housed inside a large steel tank that is pressurized to approximately 180 psi with an insulating gas to help prevent electrical discharges and to protect lab personnel.

Voltage Control
The Corona System

- To be useful in nuclear physics, the particle accelerator must be able to maintain an extremely constant accelerating voltage over a very long period of time. Regardless of the method of charging the terminal, it is necessary to devise a way to compensate for variations in the terminal voltage due to charging inconsistencies, minor discharges, etc. This is done in nearly all Van de Graaff accelerators by using a coronal discharge system.

- In our case, this system consists of a set of very sharp needles mounted inside (but electrically isolated from) a mushroom shaped electrode. The entire assembly is mounted on a long rod through the wall of the pressure vessel so that the needles can be moved close to or far away from the terminal electrode.
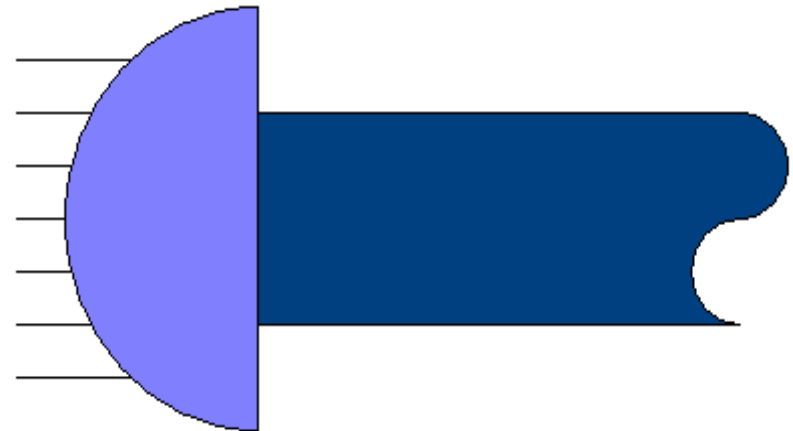
Corona System

- As the needles are moved toward the terminal, a coronal discharge is established, with a small amount of charge continually flowing from the terminal to the tips of the needles, due to the breakdown of the electric field at the very sharp points.

- This current flows from the needles through an electrical circuit that contains a "radio tube", which acts as a variable resistor. By controlling the amount of bias on the grid in the tube, we can either inhibit or enhance the amount of current flowing through the needles.

- This can be done in a very rapid time frame, and by controlling the grid bias we can control the corona current, and this allows us to account for variations in the terminal voltage.

- Note that this corona current tends to reduce the terminal voltage, and so must be replaced by the charging current.

Measuring the Terminal Voltage
The Generating Volt Meter

- The terminal voltage can be measured in real time by a device known as a Generating Volt Meter.

- This device is mounted in the tank wall, and the rotor blades spin in front of the stators, alternately covering and exposing the various stator plates.

- As the stators are exposed to the electric field of the terminal, an electrical signal is generated that is proportional to the terminal voltage.

Rotor

Stators

Side View
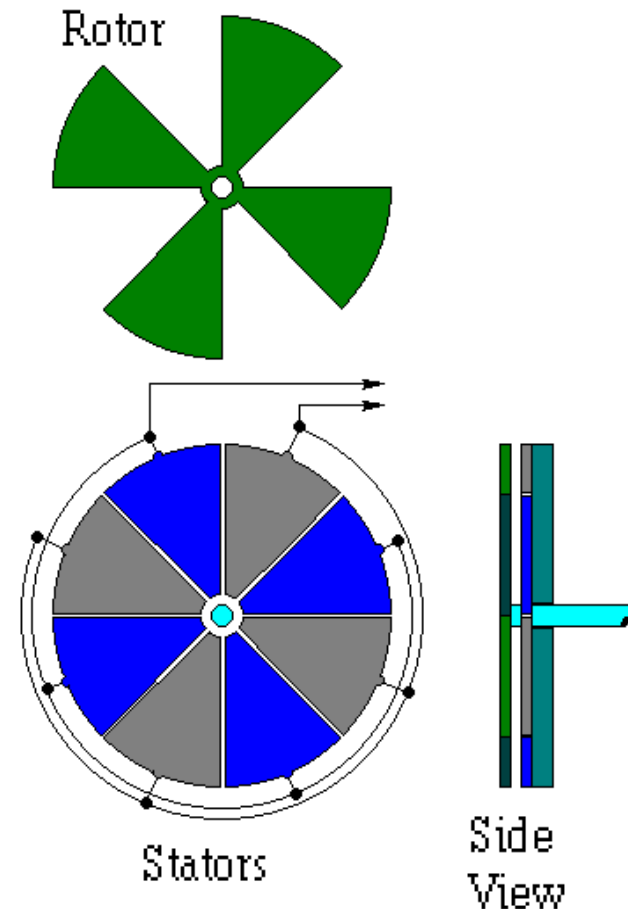
Terminal Voltage Stabilizer

- To stabilize the terminal voltage, an electrical circuit known as the stabilizer is used. It is a feedback circuit, meaning that information derived from the terminal voltage is used to control the terminal voltage. There are two modes of operation, known as Generating Voltmeter (GV) Control and Slit Control.

- In GV Control, the terminal voltage as measured by the Generating Voltmeter is compared to the terminal voltage specified by the experimenter via a setting on the front panel. The difference between the measured voltage and the requested voltage is used by the stabilizer to adjust the corona tube grid bias. For example, if the measured voltage is too high, the stabilizer adjusts the corona tube grid bias to allow more current to flow through the corona needles, reducing the terminal voltage until it agrees with the requested value.

- Note that the corona needles are not moved by the stabilizer circuit. Only the corona tube grid bias is altered by the stabilizer.

Time for a short break

FN Tandem Accelerator

- The FN Tandem accelerator is a special type of Van de Graaff accelerator, in that it requires a **negatively** charged beam produced by an ion source external to the accelerator.

- By forcing this **negatively** charged input beam to change charge states during its trip through the accelerator, we can produce <u>two</u> accelerations "for the price of one".

- This allows us to produce much higher beam energies for a given terminal voltage.

- The disadvantage to this system is that **negatively** charged beams are very difficult to produce.

Input Negative Beam

- **Negatively** charged beam is produced by an external ion source and is injected into the FN Tandem accelerator.

- The ion source produces beams with one extra electron, so the charge state of the beam as it enters the FN Tandem accelerator is q = -1.

- This beam accelerates towards the positive potential at the terminal, and gains an energy given by

$$|qV| = (1) \text{ x Terminal Voltage}$$

Inside the Terminal
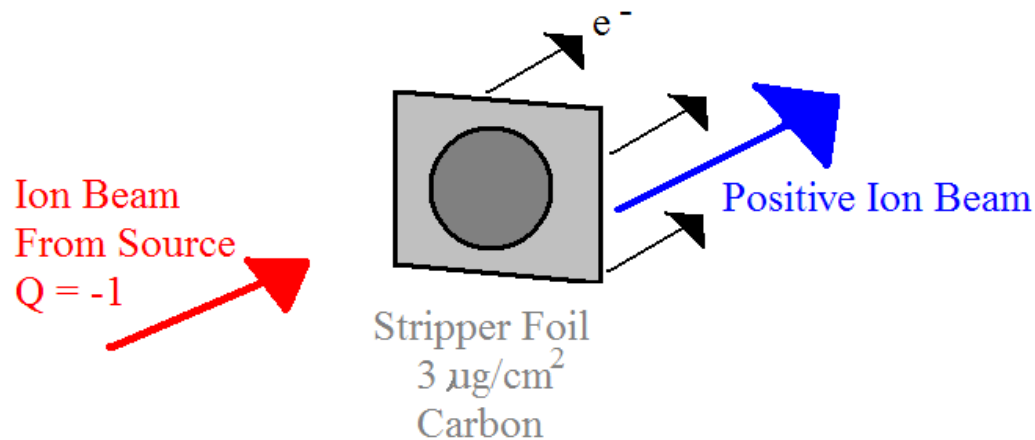
- As the incoming **negatively** charged beam accelerates to the terminal electrode, it is forced to pass through a thin carbon foil placed in the path of the beam at the center of the terminal region. Electrons are stripped from the ions in the beam, producing a distribution of **positively** charged "beams" in various charge states.

Positive Beam

- These positively charged beams accelerate <u>away</u> from the positive terminal, gaining an additional energy given by Q_{out} x V

- In general, there will be several output beams, one for each charge state populated by the stripper foil, and each of these beams will exit the accelerator with a different energy.

A Specific Example

- Suppose that there is some particular nuclear reaction that you wish to study, for any of a number of reasons. The specific nuclear physics involved will lead to a choice of ion beam and will also specify the energy required.

- For example, suppose the experiment you wish to conduct requires a beam of ^{16}O ions at an energy of 62 MeV.

The SNICS Ion Source

- You could get a beam of $(^{16}O)^{-1}$ ions from the SNICS Ion Source. SNICS is an acronym for
    - **S**ource of
    - **N**egative
    - **I**ons by
    - **C**esium
    - **S**puttering
- The SNICS Ion Source operates at about 80 kV below ground, so that the beam exiting the ion source has an energy of approximately 80 keV.

FN Tandem Accelerator

- For our FN Tandem, the "comfortable" operating range for the terminal voltage is

  2 MV – 10 MV.

- Below 2 MV, transmission of the beam through FN Tandem is poor (< 40 %) due to optical effects.

- Operating the FN Tandem above 10 MV is possible, but sparking (spontaneous discharging of the terminal voltage) is more likely and the entire system may be less stable.

- Maximum voltage to date: 10.6 MV.

Positive Ion Beam Charge State Distribution

- One can calculate the expected charge state distribution as the input beam strikes the stripper foil. The results depend upon the energy of the beam and the type of ion. For example, the charge state distribution for $(^{16}O)^{-1}$ ions with an energy of 8 MeV at the terminal is

- 4^+ 11%
- 5^+ 40%
- 6^+ 38%
- 7^+ 10%
- 8^+ ~1%
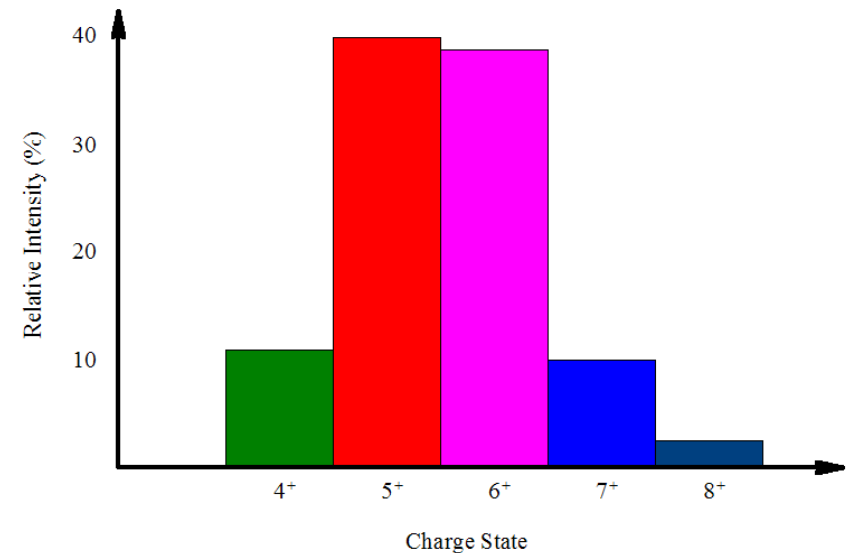
Qavg ~ 5.5+

Getting the Desired Beam Energy

- Which of these charge states can we use to produce the 62 MeV ^{16}O beam that we need for our experiment?
- The beam energy is given by $E = T(Q_{out} +1) + 0.080$ MeV (~80KeV from SNICS)
- So, if we want $E = 62$ MeV, then $T = (62 - .080)$MeV / $(Q_{out} +1)$
- Making the calculation gives the table shown here.

Q_{out}	T (MV)
4^+	12.4
5^+	10.3
6^+	8.85
7^+	7.74
8^+	6.88

Choosing the Terminal Voltage

- We can't use the 4^+ charge state because the FN Tandem can't reach 12.4 MV.
- We could try to use the 5^+ charge state at 10.3 MV, but there is just as much beam available in the 6^+ charge state, and this is easier at only 8.85 MV, well within the "comfortable" operating range for the FN Tandem.
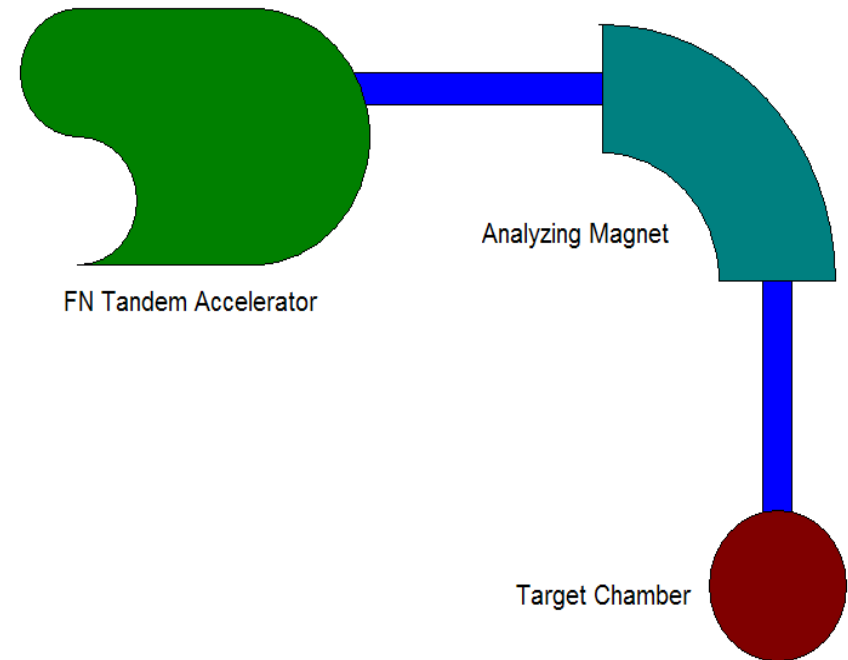
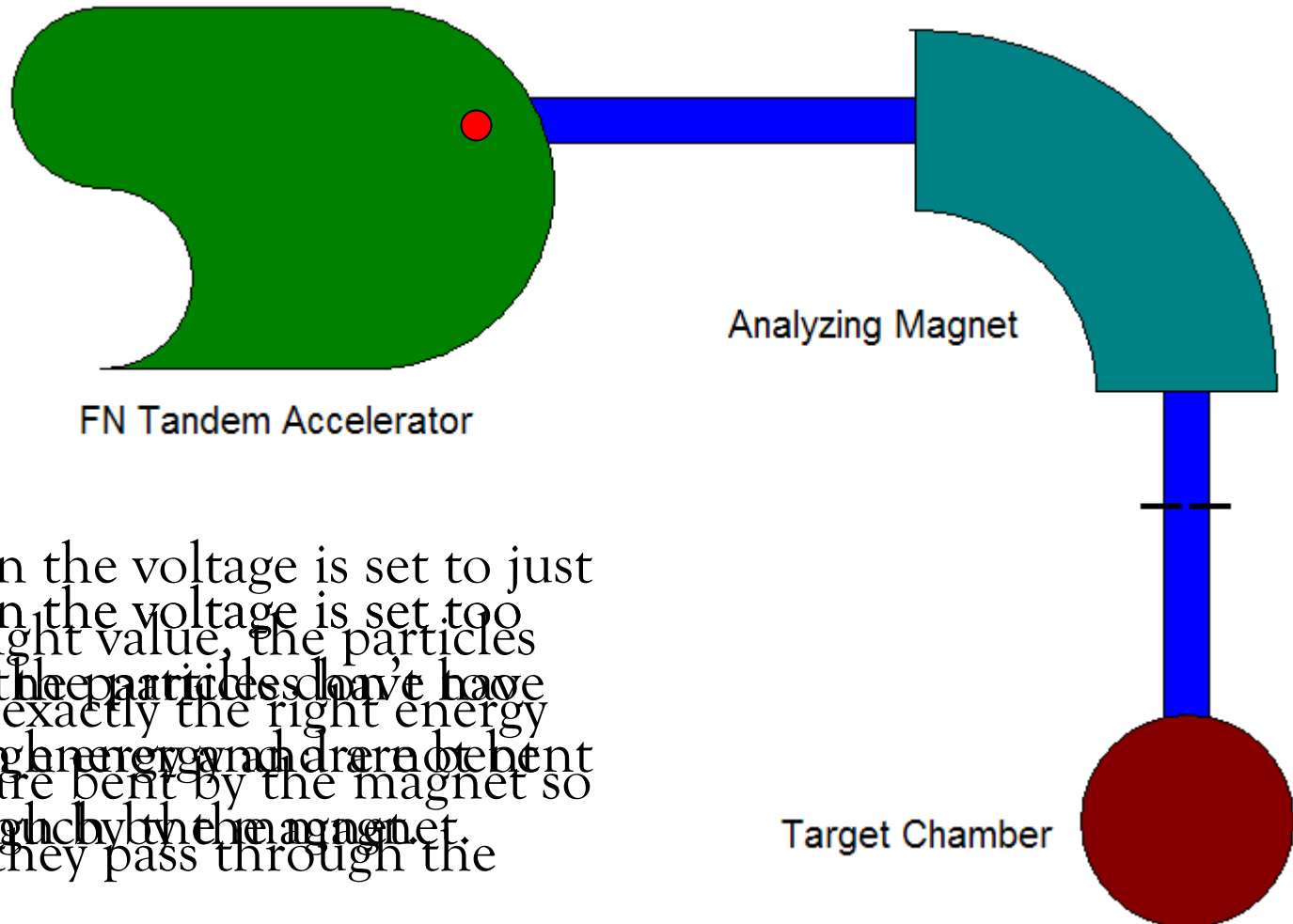| Q $_{out}$	T (MV)
4^+	12.4
5^+	10.3
6^+	8.85
7^+	7.74
8^+	6.88

Now What?

- Now that we have chosen to operate the FN Tandem accelerator at 8.85 MV so that the beam in the 6^+ charge state will have an energy of 62 MeV, what about those other charge states?

- Remembering that the beam energy is given by $E = T (Q_{out} + 1) + 0.080$ MeV (~80KeV from SNICS), we can calculate the energies of the beams from the other charge states to be:
    - $E (4^+) = 8.85$ MV $(4+1) + .080$ MeV $= 44.3$ MeV
    - $E (5^+) = 53.2$ MeV
    - $E (7^+) = 70.9$ MeV
    - $E (8^+) = 79.7$ MeV

- All these beams, plus our 62 MeV beam, will be exiting the beam line leaving the accelerator at the same time.

- How can we prevent these beams at the "wrong" energy from striking our target?

The Analyzing Magnet

- It is well known that charged particles that enter a transverse uniform magnetic field will be forced to follow a circular path, the radius of which depends upon the ratio of the particle's momentum to its charge (P/Q).
- We use a dipole magnet whose field is generated by current carrying coils above and below the beam line. By controlling the current in the magnet, we can control the magnetic field, which in turn fixes the radius of curvature of the particles entering the field. We can set the magnetic field so that only the beam of interest will travel along a path that will allow it to exit the magnet. All the other beams entering the magnet collide with the walls of the vacuum box and never reach the target.

FN Tandem Accelerator

Analyzing Magnet

Target Chamber

FN Tandem Accelerator
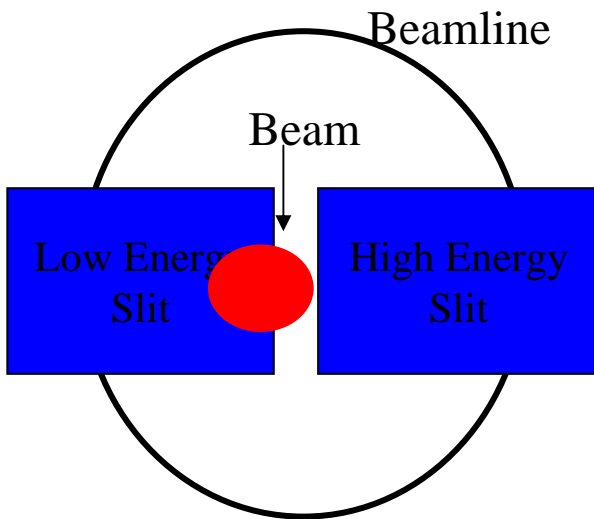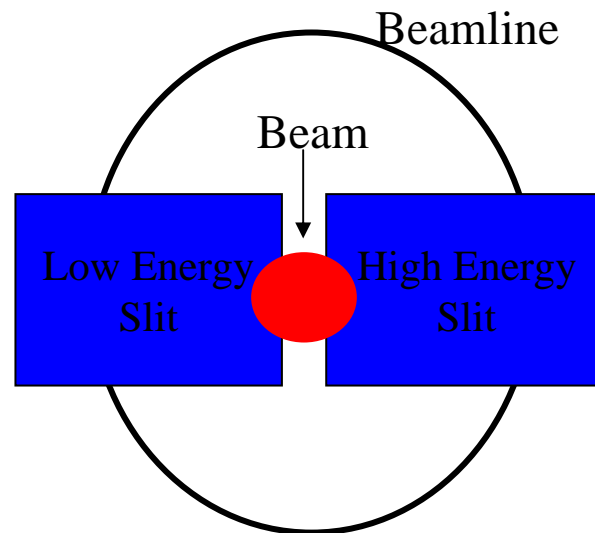
Analyzing Magnet

Target Chamber

When the voltage is set to just the right value, the particles have exactly the right energy and are bent by the magnet so that they pass through the slits.

When the voltage is set too high, the particles have too much energy and aren't bent enough by the magnet.
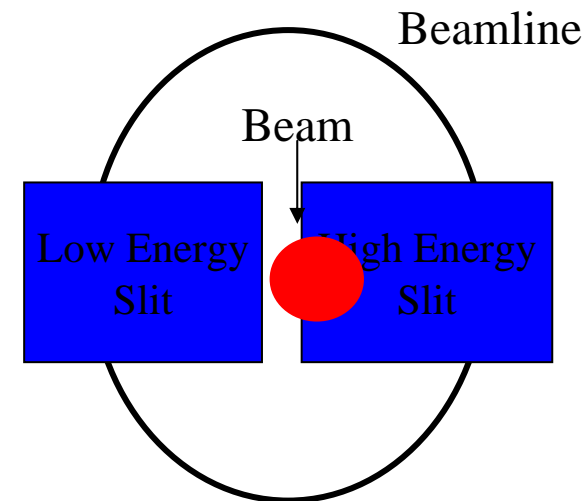
Analyzing Slits Beam View

- Looking upstream through the slits towards the magnet.

Not Enough Energy

Just Right

Too much energy

Slit Control

- We can also use the Analyzing Magnet to help control the terminal voltage of the FN Tandem accelerator.
- We place a set of metal slits near the exit of the analyzing magnet, with the opening between the slits centered on the exit of the magnet.
- If the terminal voltage drops slightly, then the particles entering the magnet have less than the desired energy, and are bent a bit too much by the magnetic field. These particles strike the slit on the "beam right" side. The difference in the amount of beam current hitting the beam right and the beam left sides is then an indication of whether the beam energy is too high, too low, or "just right".
- This signal is fed back to the stabilizer and used to control the corona tube grid bias in much the same was as is done in GV Control.
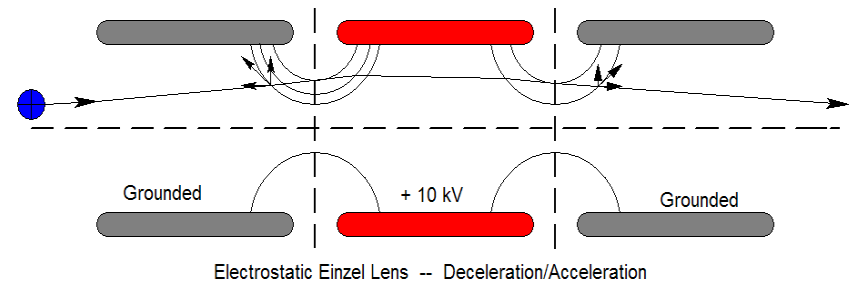
Some comments about focusing

Electrostatic Quadrupole Singlet With Positive Ions

- This slide shows the effect of an electrostatic quadrupole singlet lens. The "poles" are arranged in pairs as shown, and are charged to a high electrostatic potential.

- In general, two power supplies would be used, one to charge the positive poles and another for the negative poles.

- As can be seen in the drawing, positively charged particles will be focused in the vertical plane, but de-focused in the horizontal plane.

- Net focusing in both planes can be had by combining two such singlets to make a quadrupole doublet, where the poles are reversed in the second singlet.
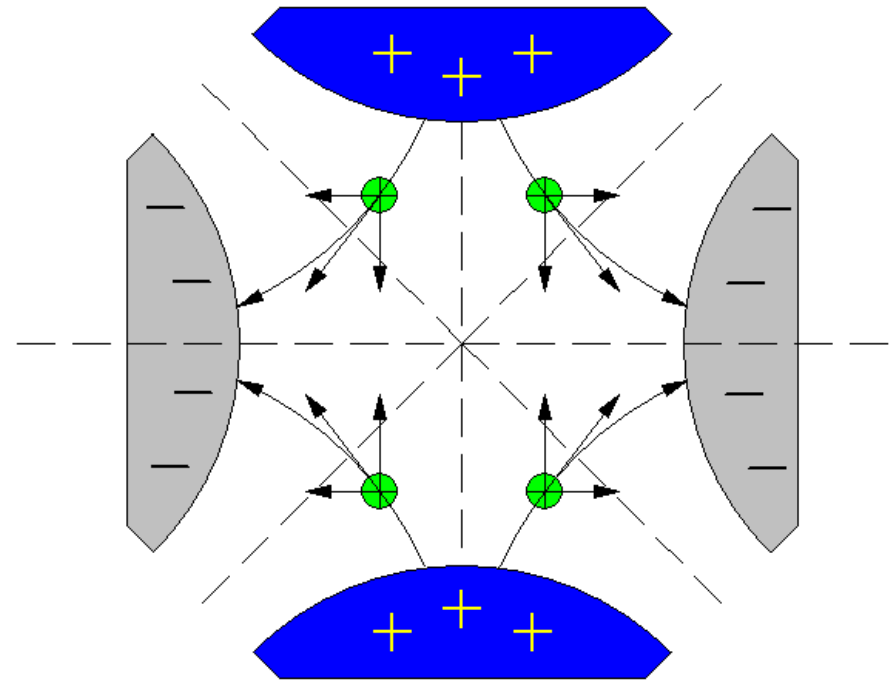
Electrostatic Einzel Lens – Decel/Accel

- This slide shows the focusing effect of a lens arrangement known as an electrostatic Einzel lens.

- It consists of three cylindrical electrodes separated by two small gaps. The outer electrodes are grounded, while the central electrode is maintained at some voltage controlled by the user.

- The forces on the charged particle as it enters the gap between the electrodes results in a net focusing, because one gap also decelerates the particle while the other gap accelerates the particle. This difference in the amount of time spent traversing the gap is responsible for the net focusing.
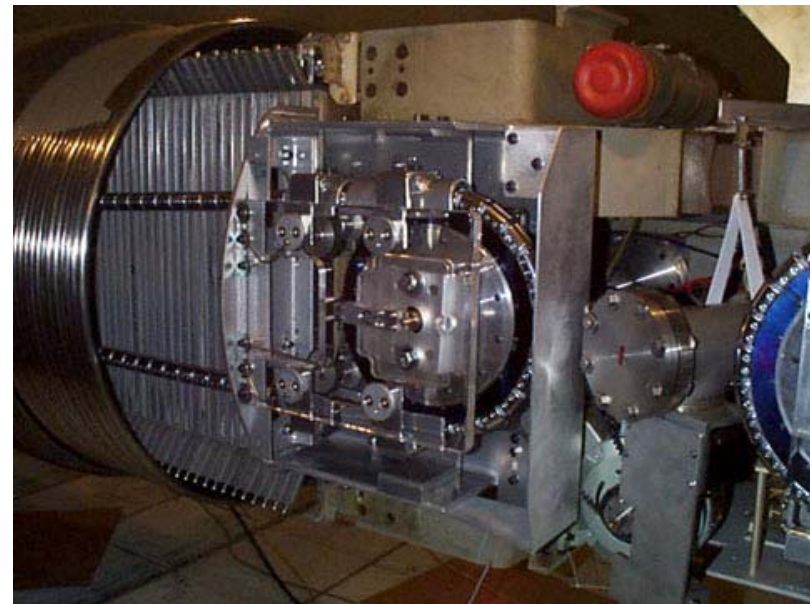
Grounded   + 10 kV   Grounded

Electrostatic Einzel Lens -- Deceleration/Acceleration
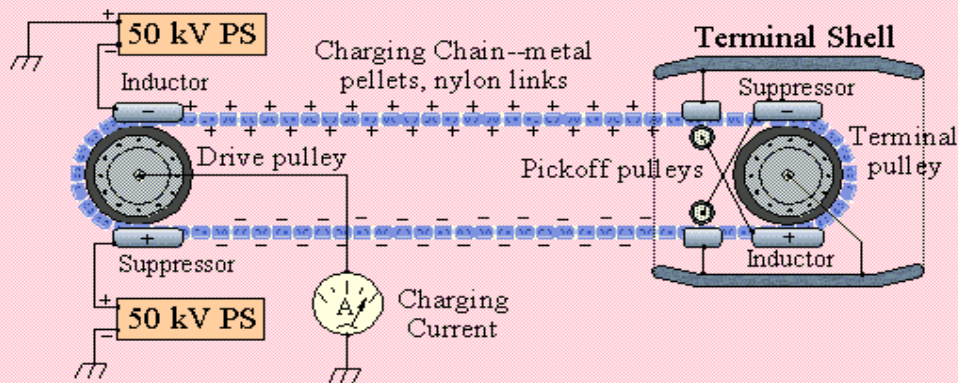
Nice Pictures of the beam
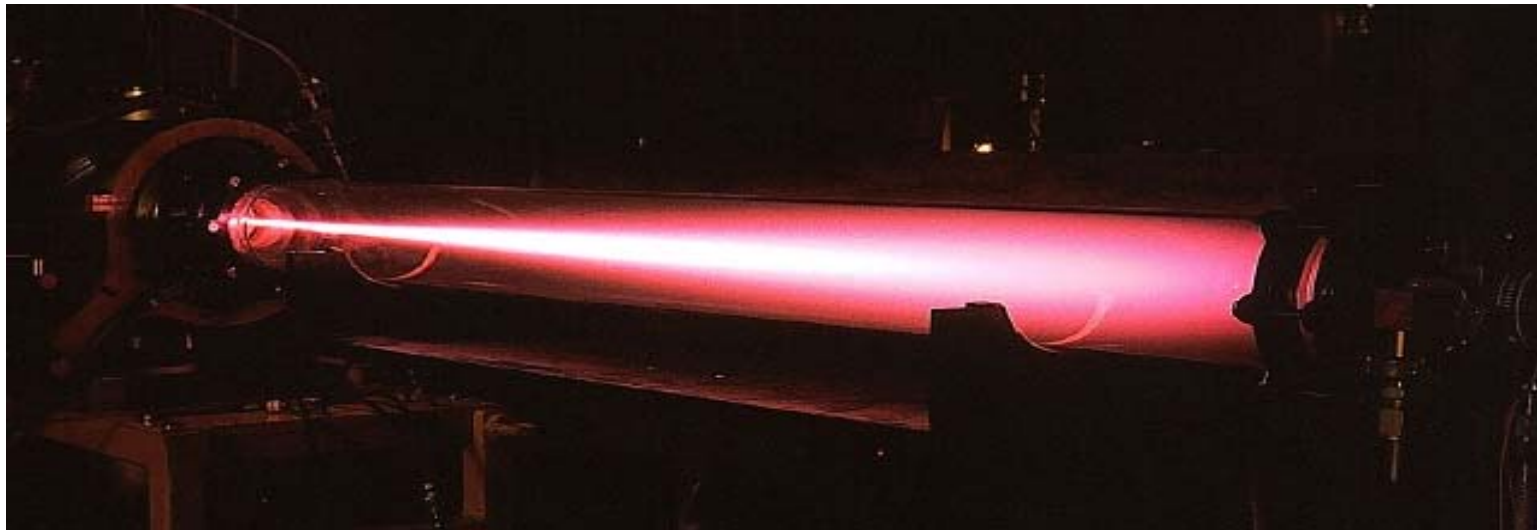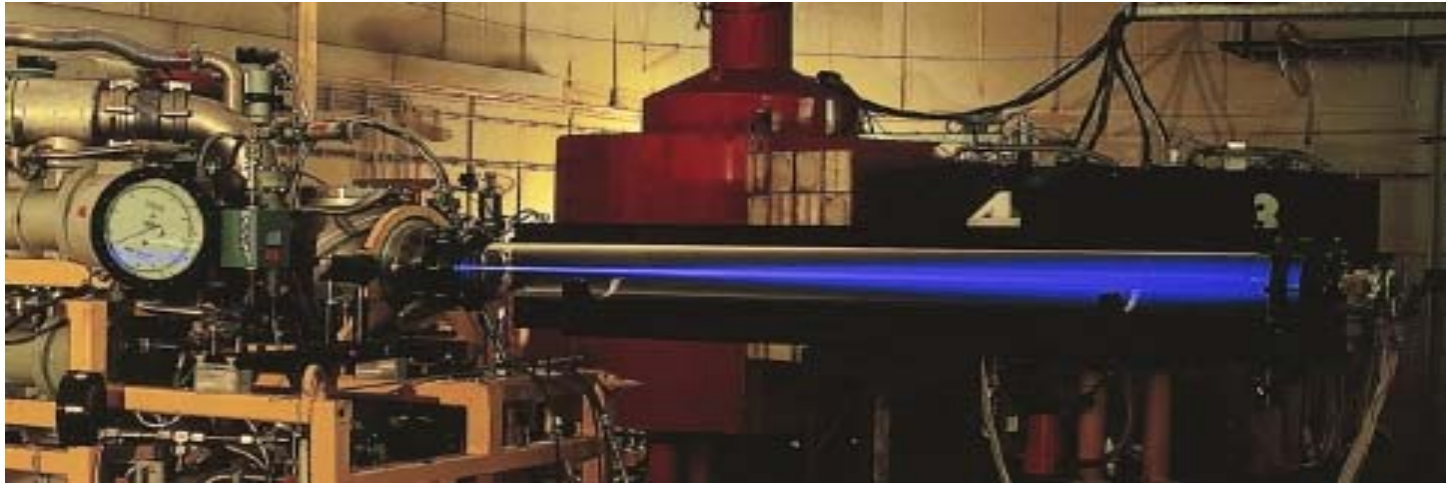
Some comments about charging

Charging the FN Tandem

The charging system used for the Tandem is known as a "pelletron", and uses charged metal pellets connected by nylon links, rather than the traditional charging belt.

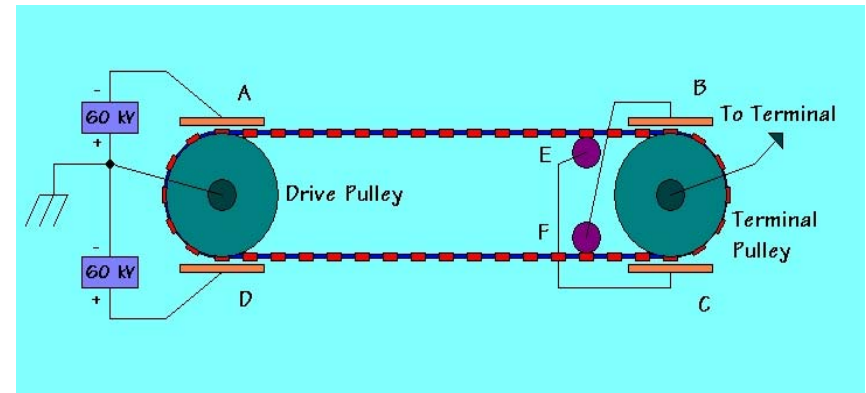**Pelletron Charging System**
(Positive configuration shown)

50 kV PS

Inductor

Charging Chain--metal pellets, nylon links

Terminal Shell

Suppressor

Drive pulley

Pickoff pulleys

Terminal pulley

Suppressor

Charging Current

50 kV PS

Inductor

Charging the FN Tandem

- As already noted, the FN Tandem accelerator requires the continuous replenishing of the charge that is flowing to ground through the column resistors.

- Originally, our FN Tandem used a rubberized cotton belt, similar to the table top model, to continuously deliver charge to the terminal. This system was remarkably effective, and was used in our accelerator for more than 30 years.

- During that time, another more stable method of delivering charge to the terminal was developed by NEC (National Electrostatic Corporation). This system, known as a pelletron system, consists of metal cylinders (pellets) linked together with nylon inter-connectors to form a "chain". Each link of the chain is slightly charged, and as the chain travels from the end of the accelerator to the terminal, charge is carried to the terminal.
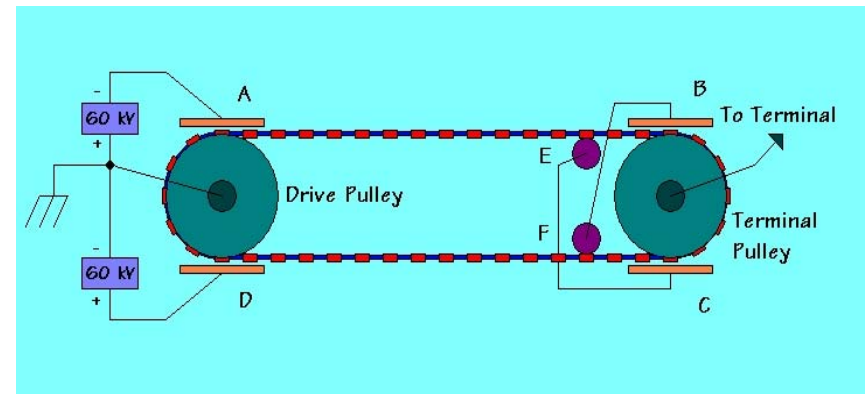
The Pelletron System

- To understand how charging is accomplished, consider the travel of a single pellet. As a pellet on the chain travels to the top of the drive pulley, it passes beneath (and very close to) the metal electrode labeled A in the drawing, known as an "inductor". This electrode is maintained at a very large negative potential by an external power supply. This large negative potential repels electrons on the pellet, which flow to ground through the drive pulley. While still being influenced by the electric field of the inductor, the pellet continues to move toward the terminal, losing contact with the drive pulley. The result is that the pellet is left with a net positive charge, having lost some of its electrons to ground through the drive pulley.

- This positively charged pellet continues to move toward the terminal, electrically isolated from the other pellets on the chain and from the accelerator column, so that the charge on the pellet is maintained.
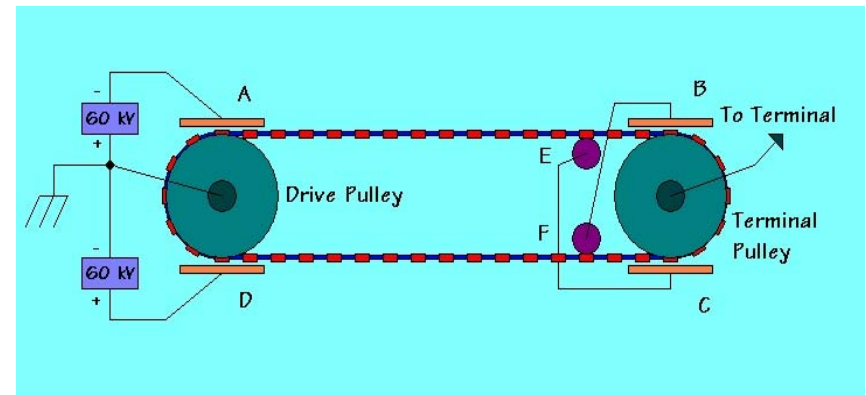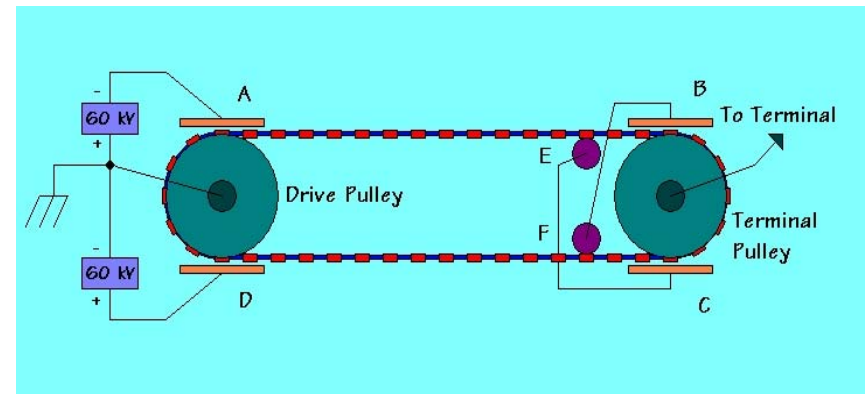
More Pelletron System

- As the pellet enters the terminal region, it comes in contact with a "pickoff wheel", labeled E in the drawing. The chain makes only very light contact with this pickoff wheel, which causes a small amount of the positive charge on the pellet to flow from the pellet to the pickoff wheel. This pickoff wheel is electrically connected to the electrode labeled C in the drawing. This electrode, also known as an inductor, becomes positively charged. Again, only a small amount of charge leaves the pellet, but the repeated action of each pellet in turn depositing a small amount of charge on the pickoff wheel is sufficient to maintain the inductor C at a large positive potential.

Even More Pelletron System

- After passing the pickoff wheel E, the pellet enters the region of the inductor labeled B in the drawing above. This inductor is maintained at a large negative potential (more about this later), which causes the positive charge on the pellet to accumulate near the upper surface of the pellet, just beneath the inductor. As the pellet nears the terminal pulley, the likelihood of a spark from the pellet to the terminal pulley is reduced because the charge on the pellet resides near the upper surface of the pellet, not near the bottom where contact with the terminal pulley is made. Once contact is made, the positive charge on the pellet flows to the terminal pulley, and is carried from the terminal pulley through a carbon brush arrangement to the terminal shell. In this way, the terminal can be charged to a very large positive potential.

- As the pellet continues to move around the terminal pulley, it enters the region of the inductor C, which is maintained at a large positive potential as previously noted. This large positive potential attracts electrons to the surface of the pellet nearest the electrode, and these electrons flow from the terminal electrode through the terminal pulley. This removal of electrons from the terminal electrode again increases the net positive potential of the terminal electrode, so that the terminal is charged by both the up and down runs of the chain. One way to think of this is that the upper section of the chain carries positive charge to the terminal while the lower section carries negative charge away from the terminal.

Enough About the Pelletron System

- As the pellet continues to move, and loses contact with the terminal pulley, it is still within the electric field of the inductor C, so that the pellet is left with a net negative charge. Just before exiting the terminal region, the pellet passes over pickoff wheel F, which causes a small amount of negative charge to be transferred from the pellet to the pickoff wheel F. The pickoff wheel F is connected to the inductor B, so that the repeated action of many pellets passing over the pickoff wheel F is to maintain a large negative potential at inductor B.

- The pellet then leaves the terminal region, travels down the accelerator column into the region of inductor D near the drive motor pulley. Inductor D is maintained at a large positive potential by an external power supply, which holds the electrons on the side of the pellet nearest the inductor, so that sparking as the pellet contacts the drive pulley is minimized. As the pellet continues, it leaves the region of the electric field of inductor D, and the electrons on the pellet flow to ground through the drive motor and the pellet is neutralized, ready for the cycle to begin again.