Pulsed power diode accelerator

Author:

Ali Obeid

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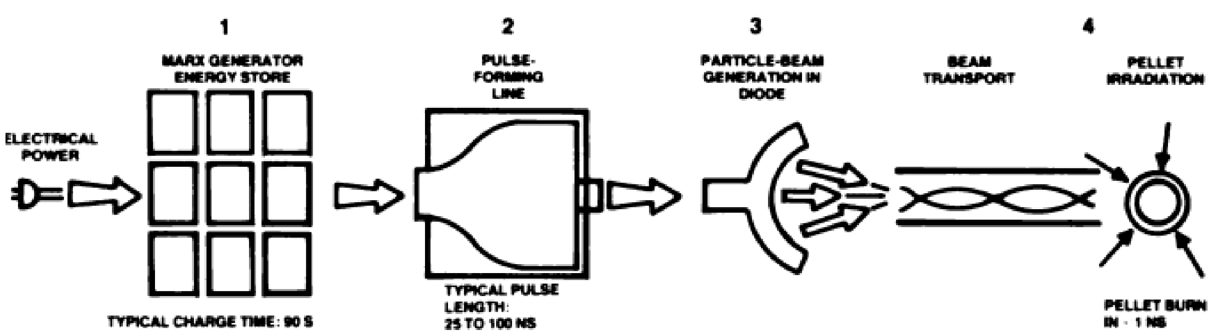
General Features:

Pulsed diode accelerators are not charged particle accelerators in the usual sense familiar from high energy physics research. Alternatively they can be considered as electromagnetic pulse compressors. The general operation of these devices involves discharging electrical energy from capacitive storage devices known as Marx generators into a pulse modulation line where a short, high-energy pulse is formed and then applied to the diode via the transmission line. An intense electromagnetic wave travels inward along the transmission line and appears on a pair of face-to-face particle accelerator electrodes. One electrode, the cathode, is charged with a negative pulse relative to the other electrode, the anode. When millions of volts are applied to the electrodes, the electric fields produced are enough to pull electrons from the cathode material into the vacuum. Electrons withdrawn from the cathode dissipate enough energy at both the cathode and anode to vaporize their surface layers and form a plasma. The cathode plasma becomes the electron source and the anode plasma provides a source of positive charge to neutralize the static field electric current of the beam. The basic components of a pulse diode accelerator include:



Basic components of a pulsed power diode accelerator.

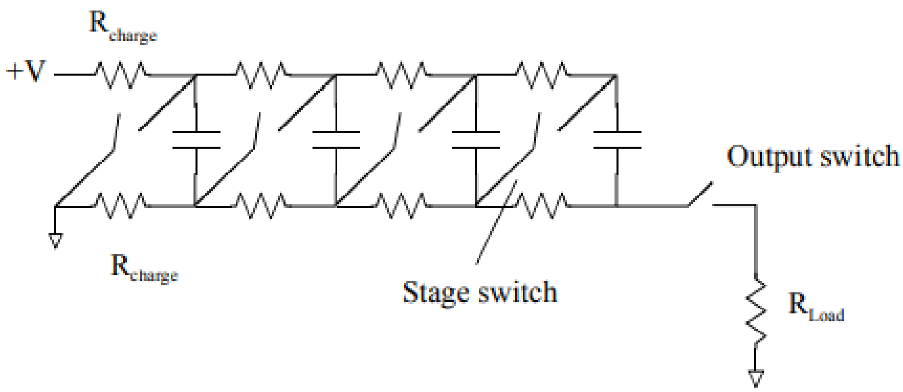
1. A capacitive energy storage system: Usually this is a Marx generator that acts as a storage device and a voltage multiplier. The Marx The alternator charges the capacitors in parallel and then discharges them in series to achieve a very high voltage. The rise time of the pulse produced by a Marx generator is too slow for ICF drive applications, so one must then compress the pulse in time.
2. Pulse forming lines: A pulse modulating network is used to compress electrical energy into a short, fast pulse, nearly doubling the output voltage in the process. This can be both one or more pulse lines and a complex transmitter such as the Blumlein network.
3. Transmission line: Then the energy pulse is transmitted as an intense electromagnetic wave through a transmission line to the diode. High voltage isolation of the transmission line is of particular concern because it determines the maximum allowable voltage pulse.
4. Diode: The diode consists of a cathode and an anode chip, separated by a short gap. When the high voltage pulse reaches the cathode, its voltage causes an intense field to be emitted from the cathode tip which produces plasma on the surface of the cathode and results in an intense current of electrons moving towards the anode. At higher energies, electrons can easily penetrate a thin anode wafer and continue to form a relativistic electron beam with radial

Currents of several mega-amperes. The polarity of the diode can be reversed and the electron current suppressed to produce an ion beam in the device.

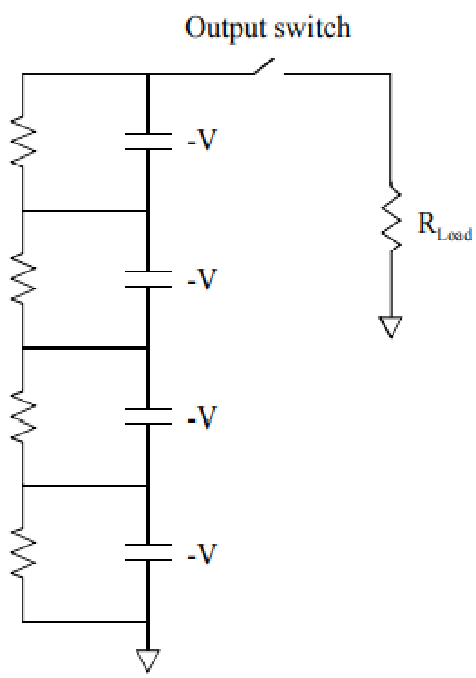
Marx generator

The term Marx Generator describes a unique circuit designed for voltage multiplication. In general, all Marx generators follow the same fundamental operation. However, similarities between Marx systems diverge in their construction and performance characteristics as a function of their application. Typical applications of the Marx generator has been with pulse charging circuits. In essence, the generator is used as an energy storage element, at relatively low voltages, and when fired, pulse charges a transmission line at a high voltage, with typical applications seen in High Power Microwave, and accelerators. Generators in this role tend to be large, as well as slow devices. Smaller versions of the Marx generator have filled the role of trigger generator for larger systems. These generators are typically characterized by their low per pulse energies, but with several hundreds of kV. The main attraction to these pulses lies in their rise times and compact geometries. Recent work has extended the use of these compact generators into the Ultra WideBand (UWB) genre. With rise times as short as 250 ps, these compact generators are finding their way into UWB radar systems and RF weapon systems and come packages that may be hand held. The Marx circuit, on the solid state level has also found applications in laser systems as Pockel's cell drivers and trigger generators. The "credit card" devices can deliver voltages of 10's of kV, with sub-Joule energies. This paper attempts to provide a broad overview of Marx generators, their fundamental operation, and some perspective on electrical characteristics and associated volumes. Fundamental trigger techniques are presented and include information for low jitter operation. Finally, the wave-erection generator is presented.

The Marx generator is a capacitive energy storage circuit which is charged to a given voltage level and then quickly discharged, delivering its energy quickly to a load at very high power levels. A typical Marx circuit uses resistors to charge N capacitors in parallel to a voltage V,as shown in Figure 1. When triggered, the first switch voltage drops which increases the voltages across the remaining switches, causing a chain reaction of self-triggering. The capacitors are then momentarily switched into a series configuration, delivering a voltage pulse to the load that is theoretically N x V, depicted in Figure 2. The output switch is present to isolate the load while charging the Marx, and to insure full Marx erection before energy is transferred to the load. The charging resistors grade the output voltage from the charging supply during firing, providing electrical isolation.



Marx generator charging circuit.



Marx generator discharging circuit.

Marx generator:

A) Large Generators Systems Large Marx generator systems may be found in the ever-expansive high energy systems such as with the Z-machine and large HPM systems, and often reside in very large rooms. These systems offer Mega-volts and Mega-Joules at relatively long pulse durations. The pulses are slow in their rise time (10's of ns), and due to their massive energy requirements, offer very low repetition rates (essentially single events).

B) Moderate Generator Systems Moderate Marx generators may be categorized as small room to large desktop-sized systems, offering voltages from 100's of kV to several MV's. Pulse energies may rate into the low MJ's. Pulse widths vary from 10's of ns to µs. Their rise times typically remain slow, on the order of several ns to 10’s of ns. However, repetition rates are more achievable and as high as several 10’s of Hz.

C) Compact Generator Systems Compact Marx generators fit into the range of handheld to desktop-sized systems. These systems over relatively low pulse energies, < 10 J – 1kJ, and high voltages of 100’s kV to MV. Fast rise times, 100’s ps, are achievable, as well as high repetition rates (> 1 kHz).

D) Solid State Generator Systems Solid state Marx generators are circuit board size systems with voltages up to the several kV range and less than 1 Joule energy storage. Rise times in the 100 ps range have been demonstrated. Repetition rates could potentially be in the 10’s to 100’s of kHz. Large and moderate Marx generators are typically used as pulse charging sub-systems in larger pulsed power applications. In systems such as Z pinch machines Marx generators are initial energy stores which deliver energy to a pulse compression circuit before reaching the load. Compact and solid state generators can be designed to have pulse widths that are narrow enough to drive some applications directly. These include ultra wide band antennas, jamming systems, and pulse radar systems. Multi-pulse systems can also be directly driven, with serial temporal signals spaced apart in the 10’s of ns for driving a common antenna, or phased array systems with sub-ns jitter and sub-ns phase differences firing into an array of antennas.

MARX TRIGGERING TECHNIQUES

The choice of Marx switches is dependent on the operating voltage, pulse repetition frequency, and lifetime, and switching support requirements. Solid state switches may be used in low voltage applications. However, many Marx generators operate in regimes where the only viable alternative is a spark gap. Spark gap technology is broadly split into liquid filled and gas filled systems. For both cases, the medium provides both the cooling and switching characteristics. Maximum repetition rates are achieved by flowing the medium through the switching region to carry away heat and recover voltage hold-off capability quickly. Liquid systems typically use oil or water, but can be based on a variety of other liquids. Liquid systems have excellent thermal mitigation properties. However, these systems tend to use pumps and filters to remove contamination, adding to volume and complexity. Gas systems can be based on a variety of gases, depending on repetition rates, spark gap lifetime, and safety concerns the highest repetition rate systems use high pressure hydrogen due to its ability to recover its insulating properties quickly after firing. V. REPETITION RATE ISSUES An important parameter for any pulsed power system is the time it requires after firing to recharge and be ready to fire again. Large and moderate generator systems typically have low repetition rates which are dictated by either the power supply’s ability to recharge the system or thermal stabilization of the load. Compact and solid state generator systems obtain size reductions by storing less energy per shot. Typically these systems still have reasonably high peak power levels with narrow pulse widths, so that thermal heating of the system from a single event is low. These systems tend to be operated at higher repetition rates in order to raise the average energy deliver to the load. High repetition rate systems can still be power supply limited. However, the recovery time of the switches used becomes a key concern Resistive charging works well for low repetition rates. However, the charging time required by the Marx before firing is approximately equal to 2N2 RC and the resistors reduce the charging efficiency. Therefore, for high repetition rate systems the resistors are replaced with inductors to accommodate fast, efficient charging. The addition of mutual coupling between the two inductors associated with a Marx stage can further increase the system performance. For this case, the individual inductances appear smaller during charging and larger during firing, allowing for faster charging with increased firing isolation.

MARX DESIGN EXAMPLE

The following example demonstrates key elements of designing a Marx generator for single output pulse delivery into a known real load. A first order approximation of the Marx generator circuit is a single loop LRC circuit where Leq and Ceq are the lumped inductance and capacitance of the Marx circuit and R is the load resistance. The period of oscillation for an underdamped circuit is given in equation (1) and the Marx impedance in equation (2).

$$T = 2\pi\sqrt{\mathrm{Leq\,Ceq}} \qquad (1)$$

$$Z = \sqrt{\mathrm{Leq/Ceq}} \qquad (2)$$

Critical damping is chosen as a compromise between maximum voltage amplitude and overshoot, as defined by equation 3. For this choice, the FWHM pulse width is about 80% of half the period of underdamped oscillation and that the output voltage will be near 70% of theoretical, shown in equations (4) and (5) where n is the number of stages and Vcharge is the Marx input voltage.

$$Z = R/2 \qquad (3)$$

$$\mathrm{Tpulse} = 0.8\,\pi\sqrt{\mathrm{Leq\,Ceq}} \qquad (4)$$

$$\mathrm{Vout} = 0.7\left(\mathrm{n\ Vcharge}\right) \qquad (5)$$

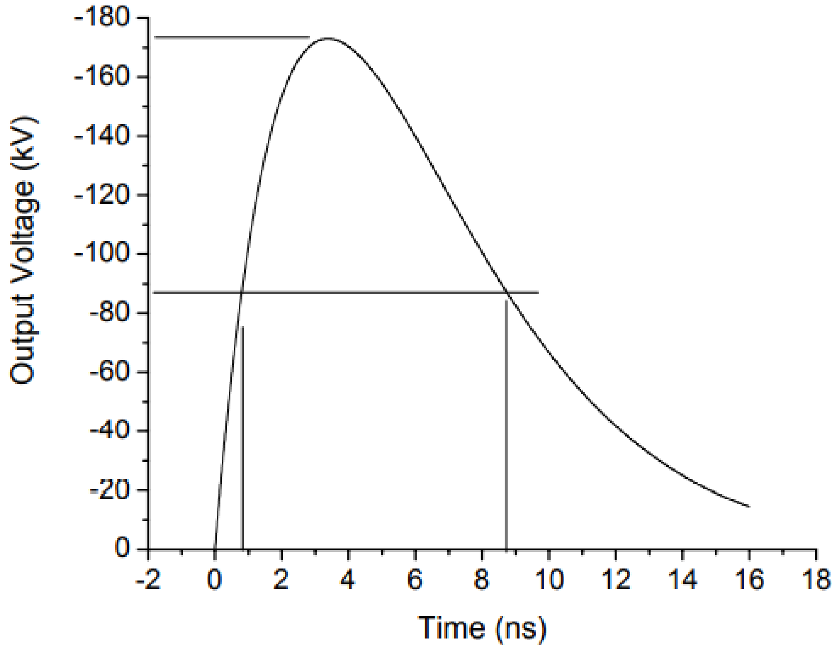
Therefore, a first pass Marx design is obtained in the following way: 1. Choose the desired Tpulse, Vout, and R. 2. Solve equations (2), (3), and (4) to find Leq and Ceq. 3. Choose n and Vcharge to satisfy equation (5). 4. Calculate the stage inductances and capacitances according to equations (6) and (7).

$$\mathrm{Lstage} = \mathrm{Leq/n} \qquad (6)$$

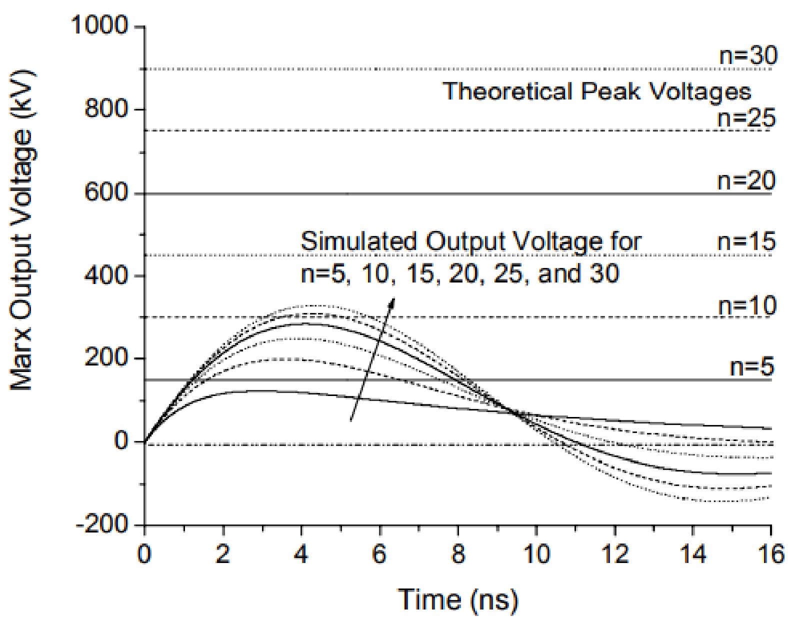
$$\mathrm{Cstage} = \mathrm{n\ Ceq} \qquad (7)$$

It should be noted that the additional inductance associated with both ends of the Marx has been neglected. They can be easily included by subtracting them from Leq before calculating Lstage. This simplification has been made to more easily show the results of adding stages in the following paragraphs. Consider the design of a Marx generator with a FWHM pulse width of 8ns with an amplitude of -170kV into 50 Ohms. These require Leq = 80nH and Ceq = 127pF. A charge voltage of 240kV is required, so an 8 stage Marx is chosen with 30 kV charging. The simulated result is shown in Figure 3. The design process shown has been straightforward, and a Marx designed as described typically performs reasonably close to specifications. It is now assumed that a Marx has been designed and constructed as described. The system works as planned, but now it is decided to increase the output voltage. It seems reasonable to construct more stages just like are presently in use and lengthen the Marx. How will these additional equivalent stages affect circuit performance, other than changing the charging time? Equation 8, derived from 2, 6 and 7 shows that the impedance of the Marx increases with n. Figure 4 illustrates that the LRC circuit model becomes increasingly underdamped. The pulse length does not change significantly, but more energy is lost in the overshoot, decreasing the voltage efficiency as shown in Figure

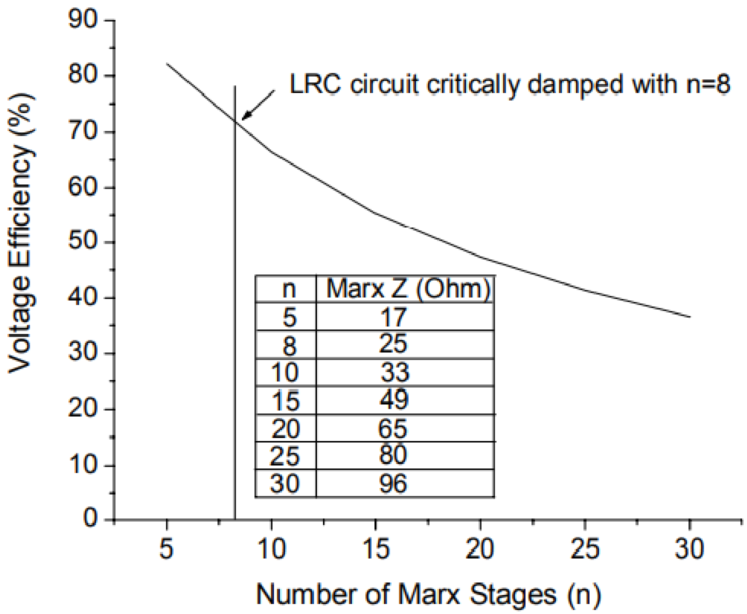
$$Z = n\sqrt{\mathrm{Lstage}/\mathrm{Cstage}} \tag{8}$$



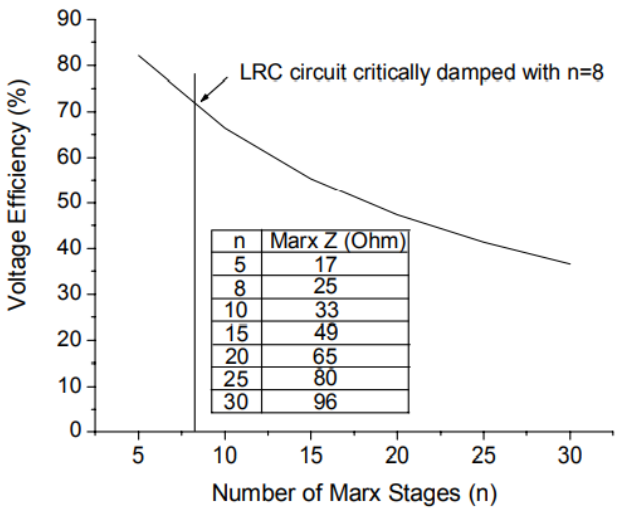
Simulation Marx generator design example.



Marx LRC circuit approximation performance when equivalent stages are added.



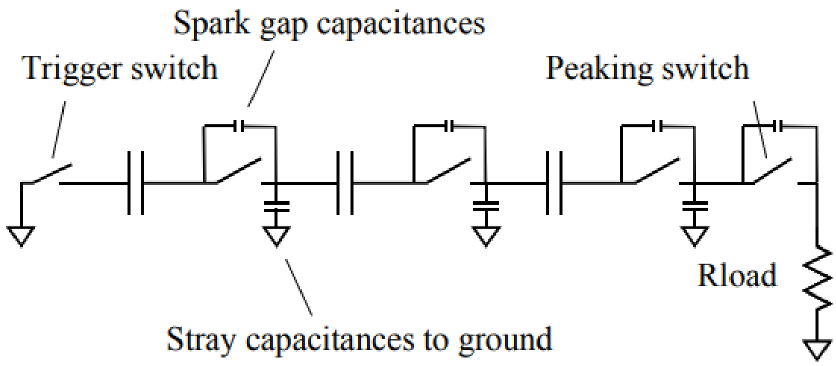
Voltage efficiency of a Marx generator as equivalent stages are added, changing the circuit damping.



Voltage efficiency of a Marx generator as equivalent stages are added, changing the circuit damping.

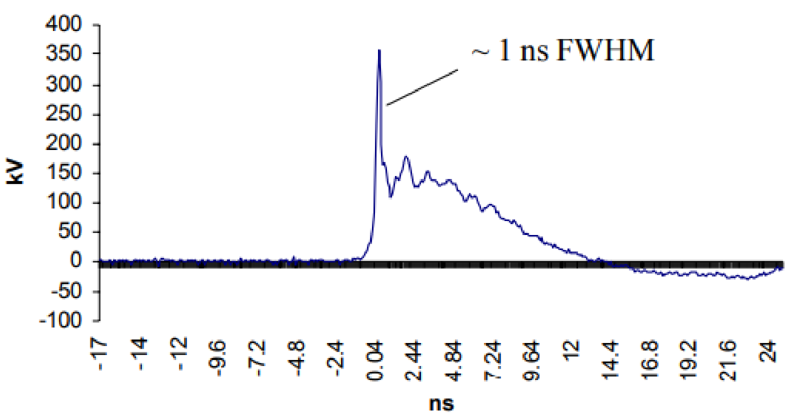
WAVE ERECTION MARX

The transient wave erection Marx shown in Figure 6 differs from the Marx circuit of Figures 1 and 2 in its use of stray capacitance effects. The general Marx circuit does not force switches to close in succession. Therefore, switches can fire randomly, adding temporal jitter to the system's performance. The transient wave Marx insures that after closure of the first switch, stray capacitances hold one side of each successive switch near ground until the switch fires. A voltage wave propagates toward the load with increasing intensity, triggering successive switches faster and faster until it reaches the load with sub-ns rise time and low jitter for output voltages of several hundred kV at moderate per pulse energies.



Transient wave erection Marx circuit.

The output waveform from a 17 stage transient wave Marx generator is shown in Figure 7. Notice the characteristic Marx output pulse shape, except for the front spike. The risetime is 250ps. A temporal jitter of 114ps RMS has been demonstrated by a 17 stage transient Marx, excluding the 15kV trigger generator circuitry.

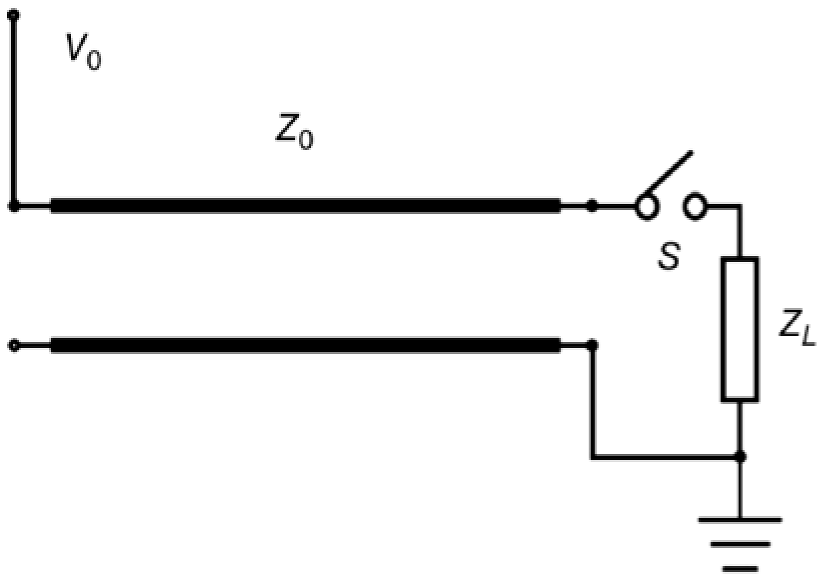


Transient wave Marx output waveform

Marx generators are effective systems for efficient voltage multiplication. For short pulse generation the Marx should operate near its critical damping due to a balance between voltage efficiency and overshoot. The transient wave erection Marx should be used where fast rise times are critical.

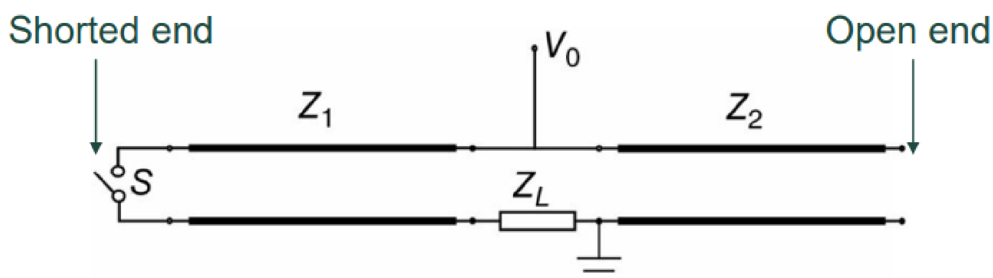
Pulse forming line (PFL)

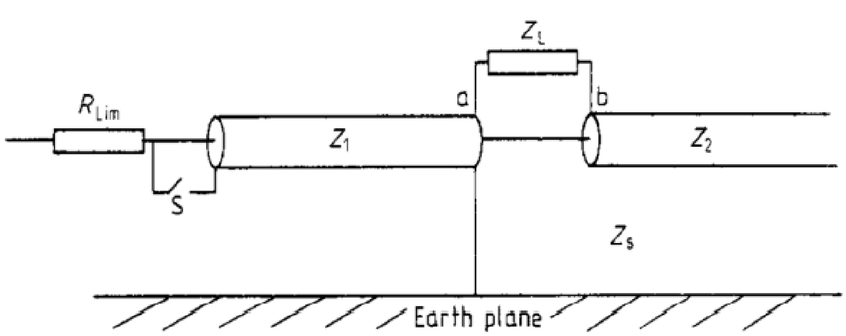
- There are numerous applications in both physics and electrical engineering for short (~10 ns < tp < 100 μs) electrical pulses. These applications often require that the pulses have a “good” square shape.
- Although there are many ways for generating such pulses, the pulse-forming line (PFL) is one of the simplest techniques and can be used even at extremely high pulsed power levels.
- A transmission line of any geometry of length ll and characteristic impedance $ZZ0$ makes a pulse forming line (PFL), which when combined with a closing switch SS makes the simple transmission line pulser.



Blumlein PFL

- An important disadvantage of the simple PFL is that the pulse generated into a matched load is only equal to $VV0/2$.
- This problem can be avoided using the Blumlein PFL invented by A. D. Blumlein.
- Two transmission lines and one switch is used to construct the generator.

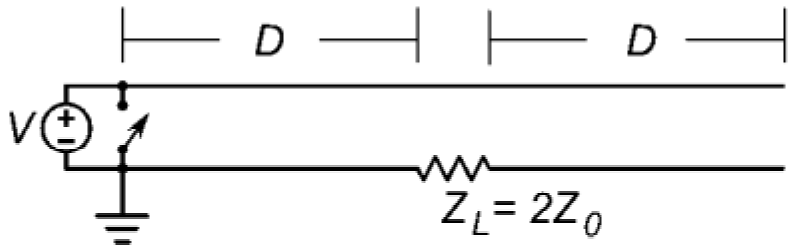


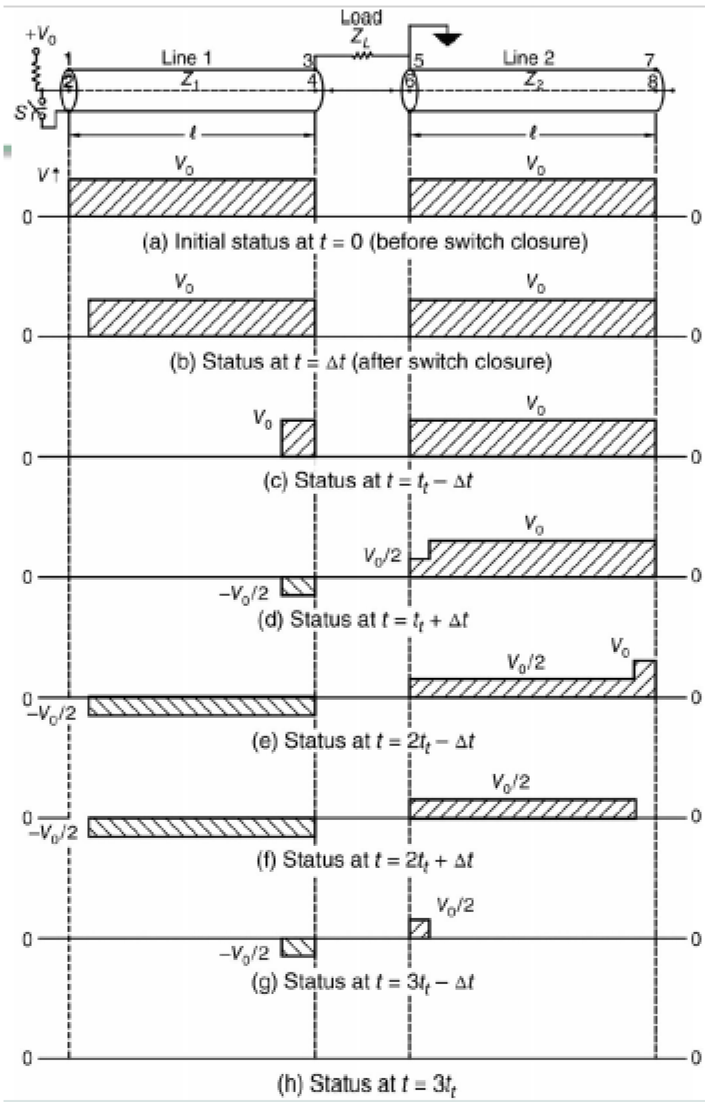


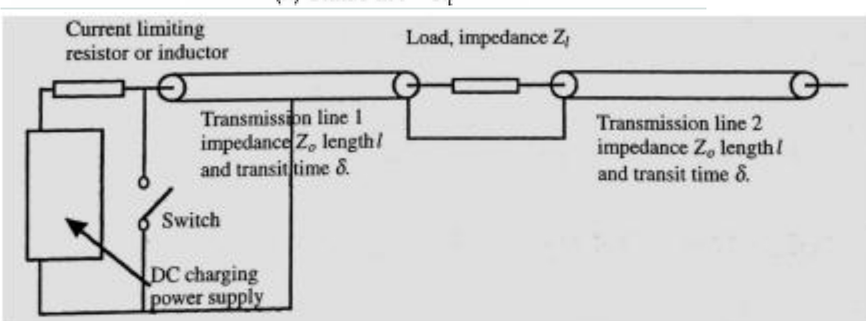
- After switch closure, the end of line 1 is effectively shorted; thus the reflection coefficient is +1.
- At the junction of line 1 and the load, the reflection coefficient is given by

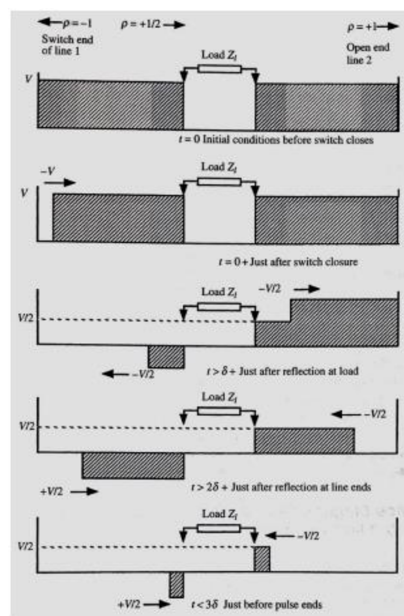
$$\rho = \frac{(Z_L + Z_2) - Z_1}{(Z_L + Z_2) + Z_1} = \frac{Z_L}{Z_L + 2Z_0} = \frac{1}{2}$$

- λ Matching condition: ZL = 2Z0









- The reflection coefficient at the load

$$\rho = \frac{Z_L}{Z_L + 2Z_0}$$

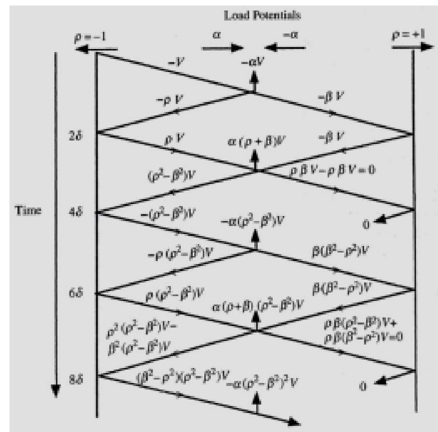
- The reflected step at the load

$$V_{-} = \rho(-V) = -V\frac{Z_L}{Z_L + 2Z_0}$$

- The step $VVTT$ transmitted to the load and the line 2

$$V_T = V_+ + V_- = -2V\frac{Z_L + Z_0}{Z_L + 2Z_0}$$

- The fraction of the step to the load and the line 2

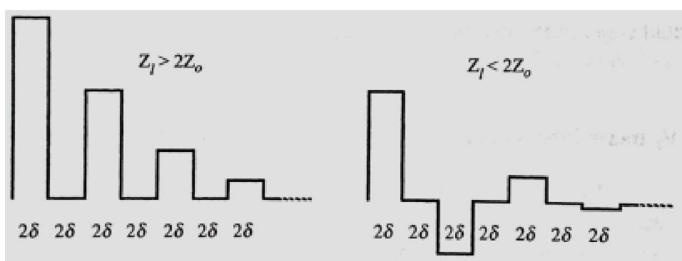


$$V_L = -2V\frac{Z_L + Z_0}{Z_L + 2Z_0} \times \frac{Z_L}{Z_L + Z_0} = -\alpha V$$

$$V_{2T} = -2V\frac{Z_L + Z_0}{Z_L + 2Z_0} \times \frac{Z_0}{Z_L + Z_0} = -\beta V$$

$$\alpha = \frac{2Z_L}{Z_L + 2Z_0} \qquad \beta = \frac{2Z_0}{Z_L + 2Z_0}$$

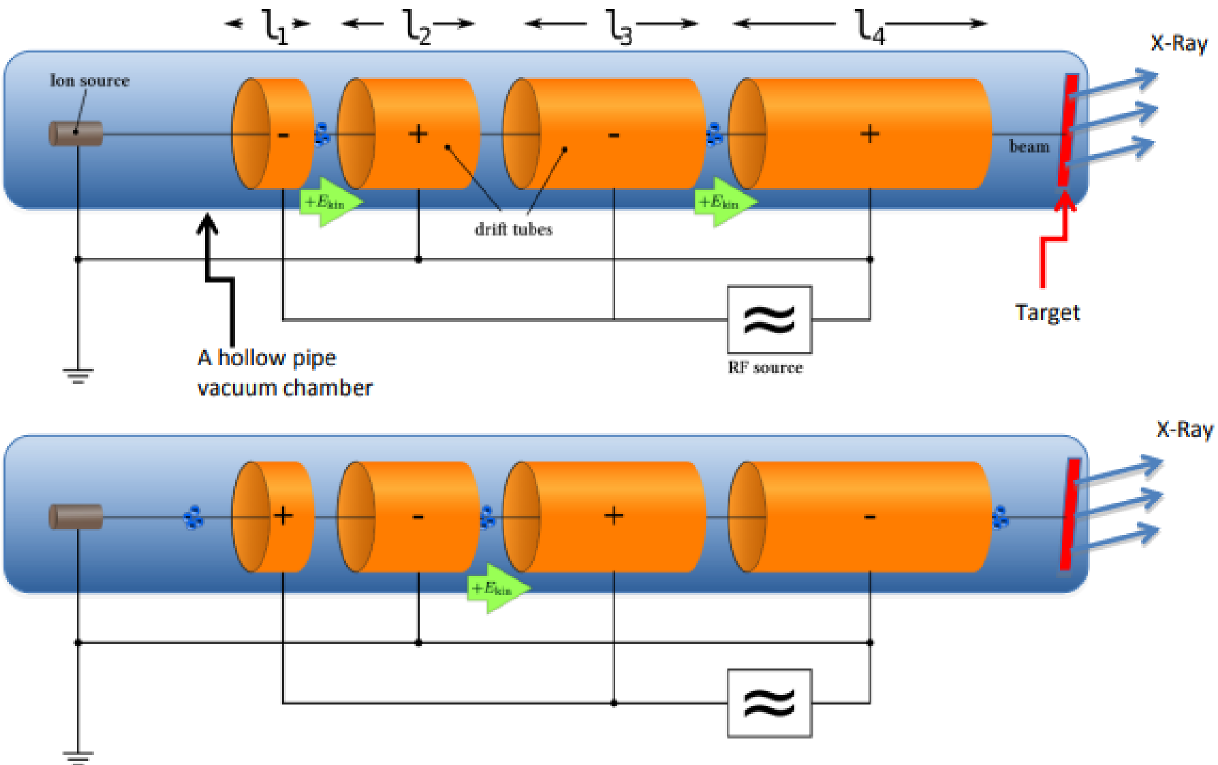
$$V_L = -\alpha V[1 - 1 + (\rho - \beta) - (\rho - \beta) + (\rho - \beta)^2 - (\rho - \beta)^2 + \cdots]$$



RF Linear particle accelerator

A linear particle accelerators have many applications: they generate X-rays and high energy electrons for medicinal purposes in radiation therapy, serve as particle injectors for higher-energy accelerators, and are used directly to achieve the highest kinetic energy for light particles (electrons and positrons) for particle physics. Linear particle accelerator (often shortened to linac) is a type of particle accelerator that greatly increases the kinetic energy of charged subatomic particles or ions by subjecting the charged particles to a series of oscillating electric potentials along a linear beamline; this method of particle acceleration was invented by Leó Szilárd.

Parts of LINAC and their functions



The particle source (“Ion source” in Figure). The design of the source depends on the particle that is being moved. Electrons are generated by a cold cathode, a hot cathode, a photocathode, or radio frequency (RF) ion sources. Protons are generated in an ion source, which can have many different designs. If heavier particles are to be accelerated, (e.g., uranium ions), a specialized ion source is needed.

A high voltage source for the initial injection of particles.

A hollow pipe vacuum chamber. The length will vary with the application. If the device is used for the production of X-rays for inspection or therapy the pipe may be only 0.5 to 1.5 meters long. If the device is to be an injector for a synchrotron it may be about ten meters long. If the device is used as the primary accelerator for nuclear particle investigations, it may be several thousand meters long.

Within the chamber, electrically isolated cylindrical electrodes (“drift tubes”) are placed, whose length varies with the distance along the pipe. The length of each electrode is determined by the frequency and power of the driving power source and the nature of the particle to be accelerated, with shorter segments (“l1” in Figure) near the source and longer segments (“l4” in Figure) near the target. The mass of the particle has a large effect on the length of the cylindrical electrodes; for example an electron is considerably lighter than a proton and so will generally require a much smaller section of cylindrical electrodes as it accelerates very quickly. Likewise, because its mass is so small, electrons have much less kinetic energy than protons at the same speed. Because of the possibility of electron emissions from highly charged surfaces, the voltages used in the accelerator have an upper limit, so this can't be as simple as just increasing voltage to match increased mass.

One or more sources of radio frequency energy ("RF source" in Figure), used to energize the cylindrical electrodes. A very high power accelerator will use one source for each electrode. The sources must operate at precise power, frequency and phase appropriate to the particle type to be accelerated to obtain maximum device power.

An appropriate target. If electrons are accelerated to produce X-rays then a water cooled tungsten target is used. Various target materials are used when protons or other nuclei are accelerated, depending upon the specific investigation. For particle-to-particle collision investigations the beam may be directed to a pair of storage rings, with the particles kept within the ring by magnetic fields. The beams may then be extracted from the storage rings to create head on particle collisions. Additional magnetic or electrostatic lens elements may be included to ensure that the beam remains in the center of the pipe and its electrodes. Very long accelerators may maintain a precise alignment of their components through the use of servo systems guided by a laser beam.

How it's Work

Ion source gives bunch of electrons which are then accelerated towards first drift tube (Bottom scheme in Figure) because of their negative potential and drift tube's positive potential. When electrons comes inside tube, in that moment RF source shifts its polarity. First drift tube then becomes negatively charged and second drift tube positively charged. Electrons comes outside of tube because of its inertia and in that moment they are pushed with first drift tube and attracted by the second one in the same direction (Top scheme in Figure). As electrons are accelerating, their velocity becomes bigger and they travel longer distance in the same time. That is the reason why drift tubes must be longer as electrons comes closer to target; because of their greater velocity. If very great velocity is needed, because of long drift tubes and big number of drift tubes, linac must be very long. As the particle bunch passes through the tube it is unaffected (the tube acts as a Faraday cage), while the frequency of the driving signal and the spacing of the gaps between electrodes are designed so that the maximum voltage differential appears as the particle crosses the gap. This accelerates the particle, imparting energy to it in the form of increased velocity. At speeds near the speed of light, the incremental velocity increase will be small, with the energy appearing as an increase in the mass of the particles. In portions of the accelerator where this occurs, the tubular electrode lengths will be almost constant.

Electrons gun:

Electron guns comprise a cathode, where the electrons are produced. The cathode is at a high negative potential, typically in the range -30kV to -150kV. There is a vacuum gap between the cathode and an anode, which is at ground potential. The anode has a hole in it, so the electrons are accelerated towards it and then pass through the hole. They then travel at a constant speed (usually a third or more of the speed of light) until they impact on the work piece or target, where they release their kinetic energy as heat and X-rays.

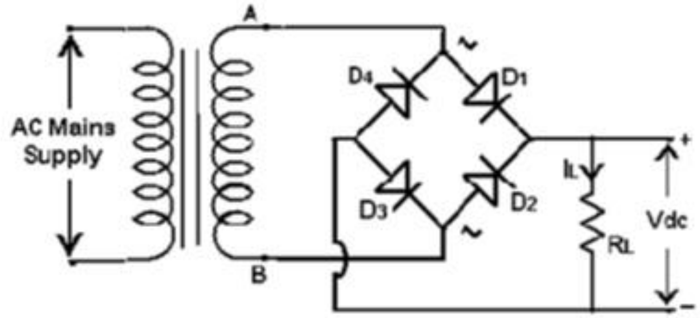
Tungsten filaments are widely used in scanning electron microscopy. Of all metals in pure form, Tungsten has the highest melting point, the lowest vapor pressure, the lowest thermal expansion and a very high tensile strength which are ideal properties for making an electron source. The operational temperature of the Tungsten filament lies around 2800 Kelvin, The difference in temperature has a direct effect on the source.

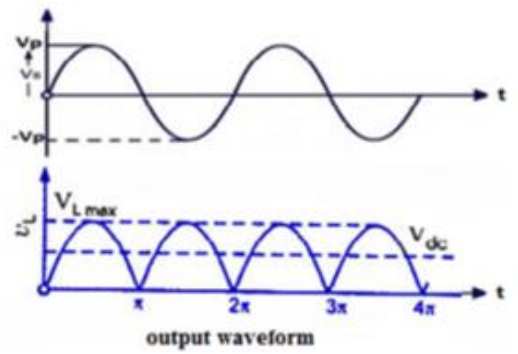
The electron beam is visible because there is a low-pressure gas in the tube. Electrons striking the gas molecules give them energy, which is then released as light.

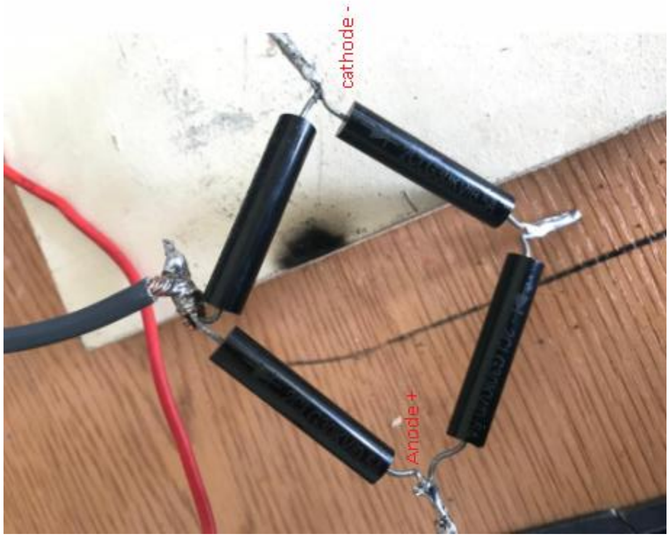
High voltage power supply:

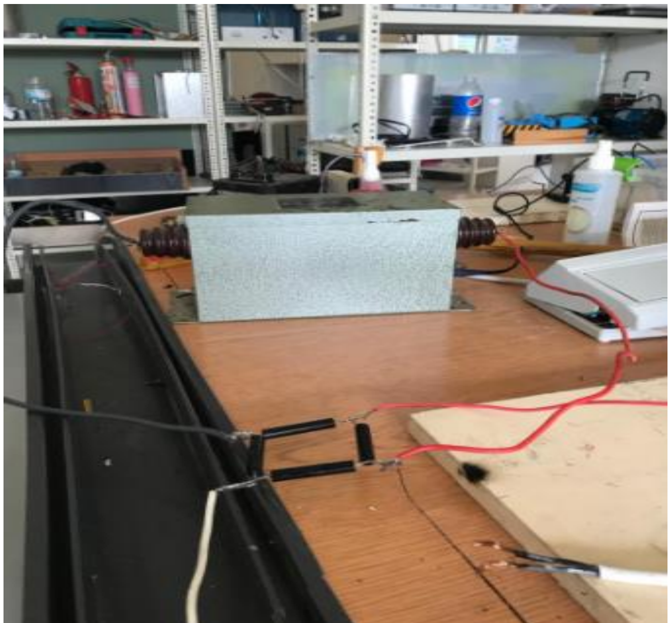
The cathode ray tube/gas discharge tube does not require any sort of specialized power supply. Any high voltage power supply that can produce over 10kV of potential difference will work.
The best type of power supply to use would probably be a (roughly) 20kV DC flyback transformer using a low current driver like a 555 oscillator and MOSFET. In fact, almost any of the "quick high voltage power supply" instructables we have here should work. However, we did not have a flyback power supply on hand, so I used a rectified sign transformer.

We’ve included an electrical schematic that shows how to hook the diodes up to the transformer.



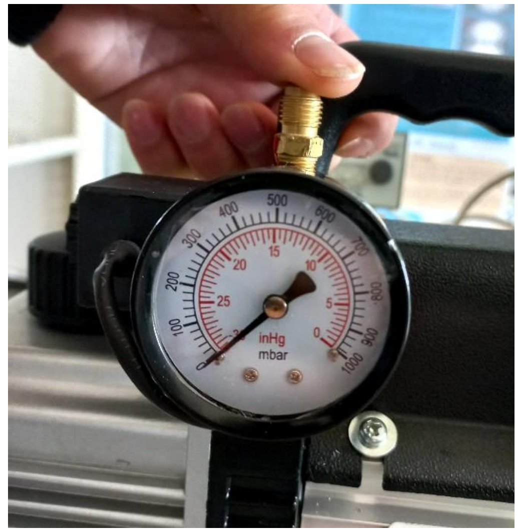






Transformer (12kv, 30 mA, 50hz)

Vacuum of the tube accelerator:



Arnocanali pump

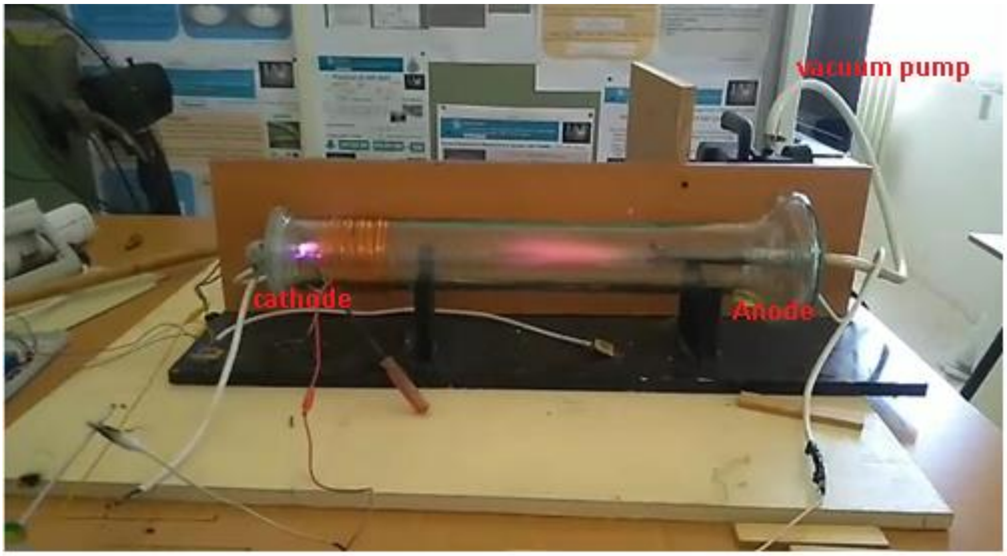
Slit accelerator anode connected:

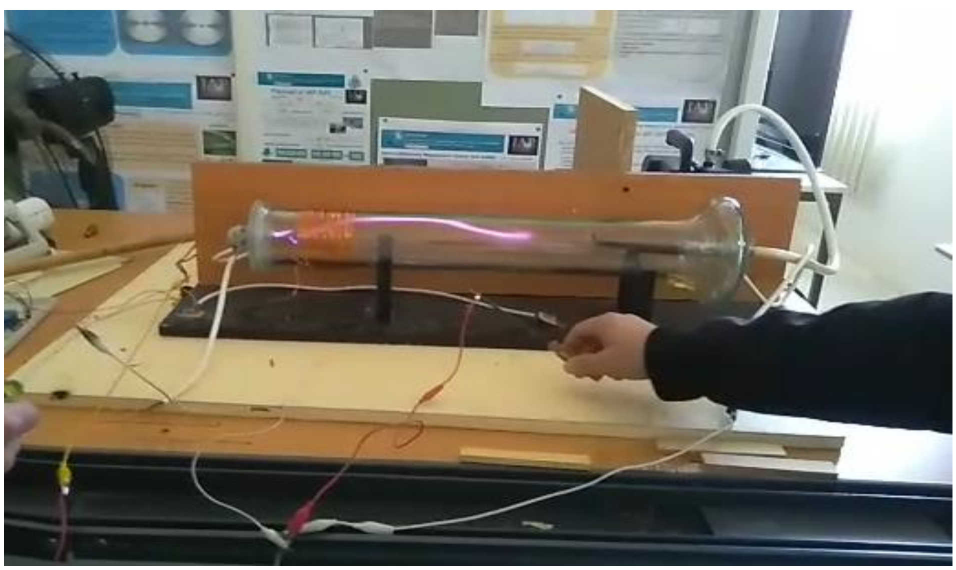
When the slit anode is connected, the electrons are accelerated and then pass through the slit.

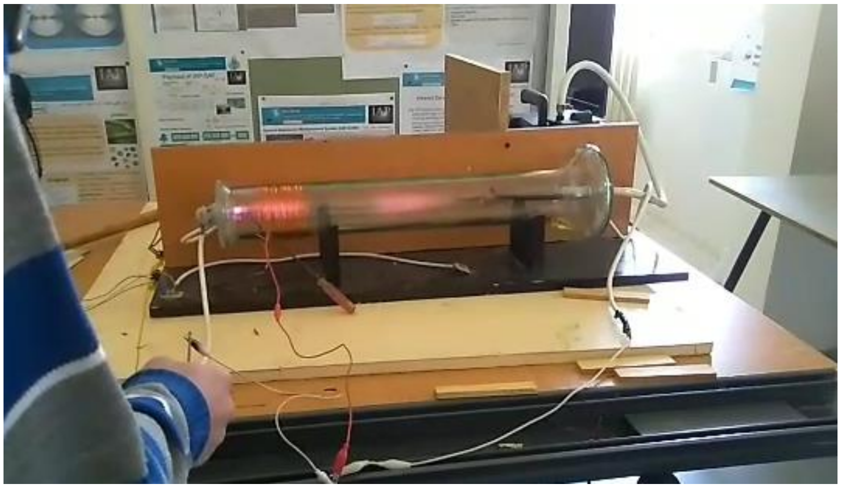
Slit accelerator anode disconnected:

When the slit is disconnected, the electrons stayed around the tungsten filament (cathode).

Tube accelerator:







The electrons beam pass from the cathode to the anode inside the accelerator tube.