6 Charging Systems

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6.1 Introduction

Charging systems for small electrostatic accelerators fall generally into three different categories: belt-charged, chain-charged and cascade. The belt and chain charging systems are mechanical in nature and can be scaled to multi-megavolt-sized machines, while the cascade system (see Box 3) employs a high-frequency solid-state high-voltage multiplier circuit that has a practical limit of a few MV. Belts are the oldest technology for producing high voltage, and the earliest accelerators were named after the father of this technology – Dr. Robert Van de Graaff of Princeton University. Dr. Van de Graaff received a patent for this technology in 1935. Belts were relatively simple to construct and were able to carry up to 1 mA of charge on their outer surface – more than enough for most applications. They are used in electrostatic accelerators produced by HVEC, which was cofounded by Robert Van de Graaff, Denis Robinson and John Trump in 1947. In the 1960s, Dr. Ray Herb at the University of Wisconsin developed a new mechanical charging system. It consisted of a chain made up of stainless steel cylinders, coupled together with insulating nylon links. These chains were capable of carrying only up to 150 μA each but with greatly improved charging stability. Multiple chains are installed in accelerators requiring greater charging capacity. This system is used in the "Pelletron" accelerators manufactured by NEC.

6.2 Belt Charging Systems

6.2.1 Physical Description

The earliest belts were of simple uncoated-cotton construction. Cotton was chosen for both its electrical and its mechanical properties. It readily accepted a static charge and did not break down in the large electric-field gradient along the accelerator column. Cotton belts also were quite strong and could be used to drive an electric generator in the terminal of the accelerator. Once tensioned, they also typically did not stretch very much with time. Typical modern charging belts manufactured by HVEC consist of a cotton multi-layer carcass, which has been coated with a vulcanized rubber material inside and out. Belts are produced in narrow (15 cm wide) widths for accelerators that operate up to 1 MV and in wide (52 cm) widths for accelerators up to ∼20 MV. In the case of a charging belt, the primary reason for variations in the charging current delivered to the terminal is the inhomogeneity of the surface of the belt. The belts are hand made and the rubber coating is vulcanized in sections, producing a variation in thickness where the sections overlap. The charge is applied to the belt via a high-voltage biased screen or shim which contacts the belt at the grounded end of the column. Fig. 6.1 illustrates the principle.

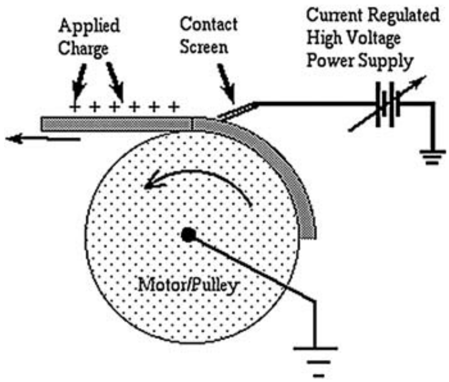

Fig. 6.1. A simplified belt charging system

The belt passes around a grounded pulley at the base of the accelerator. This pulley typically is actually an inverted motor – the armature is stationary and the outer housing rotates. A metal screen or thin shim is pressed lightly onto the surface of the belt that is in contact with the grounded pulley. The screen is, ideally, not perpendicular to the belt but at an acute angle so that wear in the screen does not produce a gap between the screen and the belt. The screen is mounted on an insulating fixture that will withstand up to 50 kV from the charging power supply under pressurized conditions. A current-regulated high-voltage power supply is connected to the charging screen and adjusted to apply the desired charge to the moving belt – up to ∼1 mA. The charge can of course be positive or negative. Positive charge will produce a positive potential on the accelerator terminal, and this is used for producing positive-ion beams. Negative charge is employed in electron accelerators. The charging screen is usually constructed of stainless steel wire mesh with between 1.5 and 3 wires per mm. The edge of the screen that contacts the belt typically has two transverse wires removed, leaving 1.5–2 mm of wire extending to contact the belt. This screen edge presents a series of sharp corona points to the outside surface of the moving belt at the drive pulley location. The screen is adjusted so that it contacts the belt lightly along the entire length of the screen to minimize wear on both the belt and the screen. The screen is not as wide as the belt and should be centered on the running belt. Because the pulleys typically are crowned, the belt will change position between rest and running conditions. It is important that the charging screen or shim not be directly exposed to the drive motor during running conditions or an electrical arc will occur – damaging the charging supply and possibly the motor bearings.

In the terminal, a similarly prepared screen which is electrically connected to the terminal contacts the belt ahead of the terminal pulley and removes the charge from the moving belt, transferring it to the terminal. Fig. 6.2 depicts a simple belt charging system for a single-ended electrostatic accelerator.

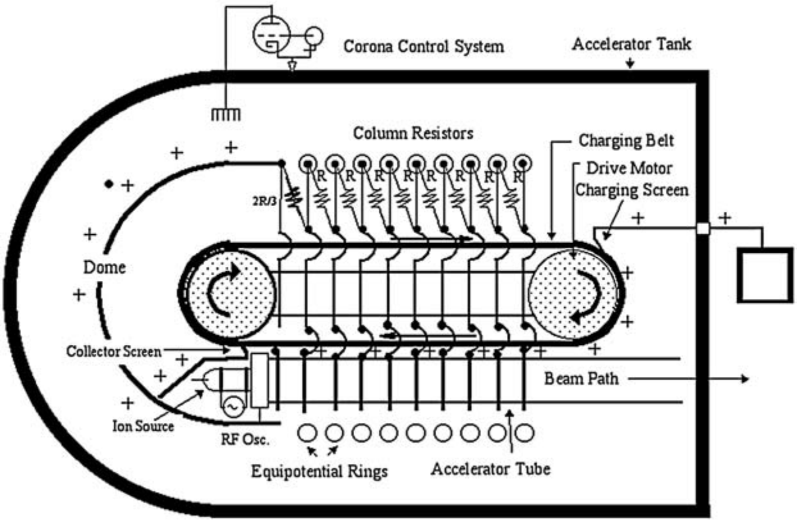

Fig. 6.2. A simple belt-charged accelerator

The DC voltage required to induce sufficient charging current on the surface of the belt is typically 5–10 kV for 100 to 200 μA of charging current. As the belt is not uniform in thickness, the charging and collector screens cannot maintain contact with the insulating rubber surface as it passes by the screen at speeds of 20–25 m/s. The voltage on the terminal will typically exhibit a pattern, which repeats every revolution, with an uncontrolled voltage fluctuation of several kV peak-to-peak, or about 0.1% of the DC terminal voltage. Figure 6.3 shows the capacitive pickoff (CPO) pattern from a model K-3000 belt-charged electrostatic accelerator.

One can observe that the pattern repeats every revolution of the belt. Also evident are about ten large fluctuations, which correspond with the ridges on the belt from the overlapping vulcanized rubber strips contacting the charging screen, causing it to bounce and not collect charge immediately after the ridge

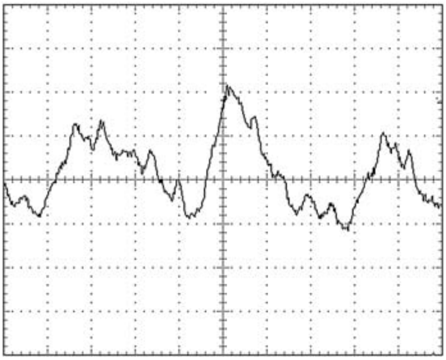

Fig. 6.3. The CPO pattern from a typical belt-charged electrostatic accelerator

passes. For this reason, some laboratories have developed modified screen systems, which utilize multiple screens, or thin metal shim stock in place of screens, to minimize these effects. These multiple screens have independent mechanical mounts that attempt to maintain each small screen in contact with the moving belt, and also independent current-regulated power supplies. These systems – while more complicated mechanically and electrically – can substantially reduce the unregulated voltage ripple from the belt charging system.

6.2.2 Maintenance

The belt charging system requires regular attention to maintain the best charging efficiency and minimum voltage ripple. The primary maintenance item is the tension in the belt. Charging belts stretch with time and as they do, the tension is reduced. This can result in excessive flapping along the column, producing excessive amounts of belt dust and occasionally damage to the belt guides. In machines with a vertically mounted belt, the reduced tension results in the belt dropping on the motor and alternator while it is running (belts normally park high when stopped). In severe cases, the belt can actually drag on the lower column crossbars, resulting in damage to the belt and to the aluminum bars. These events are typically very noticeable in the motor current and by the loss of charge along the column, as when the belt drags it dumps charge. In tandem accelerators, there are typically tension meters installed to permit the monitoring of the upper and lower drive motor tensions from outside the tank. A drop in tension can be compensated for without a tank entry by making adjustments to the motor mounts through pressure-sealed adjusting bolts. A viewer is provided to allow the technician to observe the edges of the belt on the motor. In a single-ended accelerator, adjustments require the tank to be vented and removed. The terminal shell is removed, and the several lock screws on the terminal alternator are loosened.

Typically, a hydraulic jack is provided by the manufacturer to measure the tension on each end of the terminal alternator. The jack can be used to set the tension on the lower pillow block using a manufacturer-recommended pressure reading on the gauge supplied. For an HVEC belt, the recommended tension is approximately 75 N/cm of belt width. The lower tension in a vertically installed 52 cm wide belt would therefore be between 3500 and 4000 N. The upper tension is set approximately 20% lower initially (the slight pitch is necessary to provide a vertical restoring force sufficient to offset the weight of the belt). The drive motor is started momentarily, and the position of the belt is observed. If the belt rises, the tension on the upper pillow block must be increased. If the belt drops precipitously, the upper tension should be reduced further. After several iterations, the belt should then be observed to be fairly stable. The motor can be started and allowed to attain full running speed while fine adjustments to the tension are made to prevent the belt from dropping too low on the alternator. The belt should then be stopped and the locking screws tightened. Note: do not operate the motor for more than twenty minutes in air or it will overheat. The motor is designed to operate continuously only in the pressurized environment inside the accelerator.

After several thousand hours of operation, there may be heavy deposits of belt dust accumulated on the column, which can result in instabilities along the column. To restore stable operation requires removing the belt, outer belt guides and gradient bars and perhaps also the equipotential rings. The column is cleaned with ethanol and lint-free rags. The belt can also be cleaned with unleaded (white) gasoline. This will remove contaminants such as dust and grease from the surfaces of the belt. The belt is reinstalled and tensioned as discussed previously.

6.2.3 Troubleshooting

One of the most useful tools for diagnosing problems internal to an operating accelerator is a well-calibrated CPO system. The CPO is calibrated in air (it has been demonstrated that the calibration is insensitive to pressurized tank gas) with a signal generator or simply the output from a small transformer driven from the mains via a variac in the primary. If one uses a signal of 85 V_{rms} as measured with a typical laboratory meter, this will put approximately 100 V peak-to-peak on the terminal of the accelerator if one lead of the secondary winding is connected to the tank. The output of the CPO circuit is observed on a monitor oscilloscope, and either a note of the calibration constant is made or, if adjustment of the CPO amplifier gain is possible, the gain can be adjusted to a convenient value, i.e. 1 V_{pp} (on the scope display) = 100 V_{pp} (on the terminal). With this tool, one can diagnose small discharges in the column grading resistors, poor performance of a belt due to mechanical properties of the belt, and charging-screen damage. The terminal voltage ripple can be constantly displayed on an oscilloscope at the control console.

In the case of a chain, one can usually see the actual pellet ripple and detect problems in the chain(s) by the frequency of the abnormal signal. In the case of a belt, one can usually detect the strips on the belt where the rubber overlaps and can detect areas of the belt that are not accepting charge as efficiently as the rest.

6.2.4 Troubleshooting Belt Charging Systems

The belt charging system can be divided into four major parts: the external charging power supply and controls, the mechanical charge transfer screens, the charging belt, and the belt guides in the column structure. In order to determine whether a fault lies in the external power supply or controls, one connects a high-value resistor between the output of the charging power supply and a suitable ground. The power supply is energized and the charging current increased to a normal level. If the current is stable then the power supply is working correctly; if not, it will need to be serviced. Typically, these power supplies should current-regulate to at least 0.01%.

The next things to check are the high-voltage feedthrough on the tank, and the charging and collector screens. The feedthrough can be checked with a high-voltage megohmmeter (5000 V DC recommended) for leakage. There should not be any detectable leakage ($R > 2000\,\mathrm{M\Omega}$). The charging screen should have a low-resistance connection to the feed through ($R < 10\,\Omega$), and the screen or shim should be lightly contacting the belt all along its exposed edge. If a screen is used, there should be at least one longitudinal wire removed so that there is about 1 mm of wire ends exposed to the belt. The charging screen or shim is made narrower than the belt so that in operation, the screen is not exposed to the grounded drive motor pulley. This would cause charge loss by corona to the motor, and little charge would get onto the belt. The terminal collector screen should be inspected in the same way and adjustments made to insure sufficient but not aggressive contact with the rotating belt. The collector screen should be wider than the belt to insure collection of all of the charge on the belt.

If charge loss from the moving belt is suspected (an abnormally large charging current is required to attain the required terminal voltage), one can connect the column to ground through a microampere meter, and with the terminal grounded check for charge collection at points along the column. Once located, the belt guides in that area can be inspected for proper adjustment or for contamination that is resulting in charge collection at that point. The parts should be cleaned or replaced as necessary. The belt guides (inner and outer) are normally adjusted to attain a clearance of 1.4 mm from the belt. The inner guides are typically mounted onto the column stiffener plates and are not therefore adjustable. If the clearance between the belt and the inner guides is not the same on each side of the column or from top to bottom, the terminal pulley must be moved with respect to the column by means of adjusting screws in the terminal weldment to attain proper clearance. The outer guides are installed one at a time, and the gap to the belt can be adjusted by loosening the locking screws on the end fittings and sliding them to achieve the 1.4 mm gap. The gap between belt guides should nominally be 5.6 mm, while the gap between the gradient bars (no ceramic insulator installed) should be a nominal 8.75 mm. Gradient bars and belt guides are installed in alternating fashion on each side of the belt throughout the column. The outer guides should be removed and cleaned with a petroleum distillate to remove contamination from the belt and grease whenever they are observed to be excessively dirty. Stubborn stains can be removed from the ceramic on the belt guides using a mild abrasive such as an ink eraser.

Occasionally, the bearings in the motor and alternator will need to be replaced. This will be evident if grease is observed to have contaminated the inside of the belt near either edge. When this is discovered, the belt must be removed and thoroughly cleaned to remove the grease. Continued operation can result in electrical failure of the belt by an energetic spark running the length of the belt. This frequently damages the belt, requiring it to be replaced or the damaged edge trimmed.

6.3 Chain Charging Systems

6.3.1 Introduction

The first chain charging system was developed at the University of Wisconsin in the early 1960s by James Ferry in association with Professor Ray Herb in the Physics Department. In 1965, they founded NEC and began producing Pelletron accelerators. The chains manufactured by NEC are illustrated in Fig. 6.4.

The chain is constructed of 31.75 mm diameter stainless steel tubing that is cut and has the ends rolled inwards to form 31.75 mm long pellets. The pellets are connected by insulating nylon links that are pinned into the pellets with either rivets or threaded pins and screws. There are bushings between

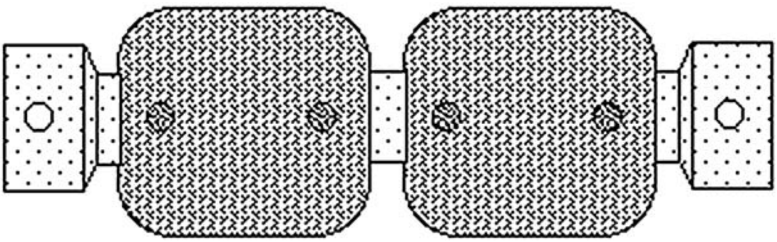

Fig. 6.4. The Pelletron chain

the inner pellet wall and the nylon link that prevent the nylon link from moving side to side and keep it centered in the pellet. The rolled ends act as spark gaps to protect the nylon links from spark damage. While early chains used an asymmetric nylon link that only allowed the chain to bend in one direction, modern chains utilize a symmetric link that permits the chain to bend in either direction. The principle of the chain charging system is illustrated in Fig. 6.5.

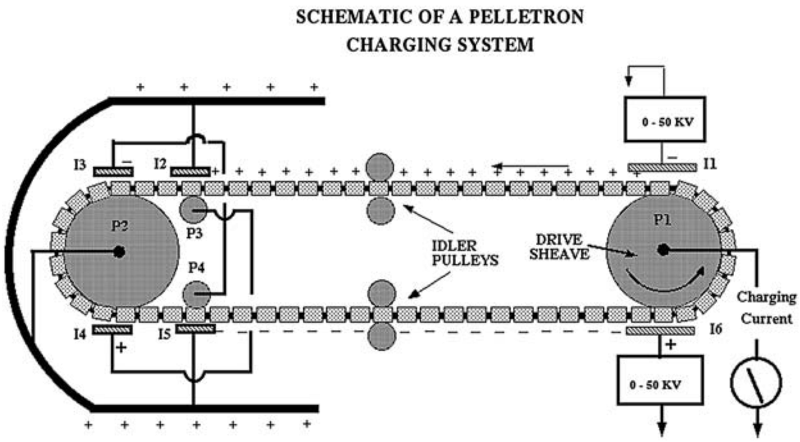

Fig. 6.5. The principle of the chain charging system

The chain rotates on two wheels, typically 30 cm diameter, and travels at about 15 m/s. Charge is induced on the chain as it leaves the grounded end of the column by a negatively charged electrode called the “inductor”. The inductor is biased by a 50 kV high-voltage power supply which is controlled remotely from the accelerator console. As no current is drawn from this supply, it only needs to be voltage regulated. The induced charge on the chain is typically between 3 and 4 μA/kV of inductor voltage. Positive charge flows through the wheel and the contact bands to the metal link – or pellet – which develops a mirror charge on the surface of the link opposite the negative electrode. As the wheel rotates, the contact between the pellet and the wheel is broken, and the positive charge is trapped on the steel pellet by the insulating nylon connecting link. The charge then redistributes itself on the outside surface of the pellet and is mechanically transported to the terminal by the rotating chain. As the charged pellet arrives in the terminal it passes through another electrode. A mirror charge is developed on this electrode that is negative in sign and equal to the inductor voltage if the gaps are the same as at the inductor. A conductive “charge pickoff” wheel located under this electrode picks up charge from the chain as it passes, and applies it to another inductor that is located on the opposite side of the terminal wheel.

This terminal “inductor” electrode becomes electrostatically positive owing to the electrons that have flowed to the pickoff wheel, and a negative charge is induced on the pellets leaving the terminal. In this way, charge is carried in both directions and the charging efficiency can be doubled. The pellet arriving in the terminal contacts the conductive rim of the terminal pulley and the trapped charge is thereby transferred to the terminal. As mentioned previously, the arriving charge is not a DC current, owing to the nature of the charging system, but it delivers a much more constant charge than belt systems typically can. For chain charging systems, the time-dependent fluctuations in the charging current are substantially less as the charge is applied to individual metal chain elements, which have a high degree of uniformity. During an open-tank maintenance, it is useful to check the charging uniformity and efficiency by grounding the terminal through a resistor, $\cong 1\,\mathrm{M\Omega}$ for instance. Charge can be applied to the chain(s) and the terminal voltage observed with an oscilloscope connected to the terminal. This works for charging currents up to $\cong 100\ \mu\mathrm{A}$ and will make apparent any problems in the charging system before closing the accelerator. It is good practice to record the results with a photograph for future reference. Figure 6.6 is an oscilloscope trace showing the magnitude of the arriving charge versus time for one chain in a typical chain charging system.

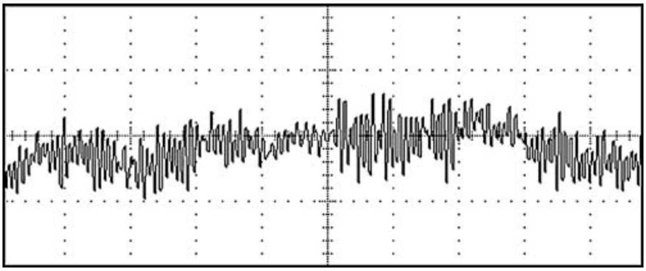

Fig. 6.6. An oscilloscope trace showing the magnitude of the arriving charge versus time for one chain in a typical chain charging system

The high-frequency ripples are due to the arrival of the individual charges on the pellets, while the slower fluctuations are due to nonuniformities in the charging and discharging wheels. 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.

6.3.2 Other Chain Charging Systems

Researchers at Daresbury Laboratory (UK) developed a different type of charging chain in the 1970s. High Voltage Engineering developed its own version of this chain system and named it the Laddertron. This chain consisted of two chains running side by side with aluminum crossbars connecting adjacent pellets. The appearance of the chain therefore resembles a ladder. This chain was a major improvement over the rubberized cotton charging belts and was installed in several new machines in Stony Brook, Orsay, Legnaro, Beijing and Ile-Ife (although that machine has never been used). This charging chain was guaranteed to carry 250 μA of charge in an accelerator with at least 30% SF_6 in the insulating gas mixture. The voltage stability is greatly improved over the belt, with 1% RMS current stability reported. The construction of the Laddertron is illustrated in Fig. 6.7.

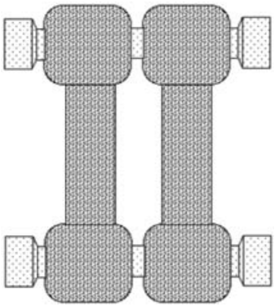

Fig. 6.7. The Laddertron charging chain

This system, however, has several significant disadvantages relative to the Pelletron system. The primary problem with this system is the weight of the chain. It is approximately 5 kg/m and requires a tension of approximately 900 N for stable running. This higher tension produces significantly higher rates of wear on the bushing in the insulating nylon links, and this results in a significantly shorter lifetime – on the order of 5000 hours (compared with perhaps 30 000 for a Pelletron). The chain is repairable, however, and can be disassembled to replace the worn bushings. This is a time-consuming task, as in an FN the chain consists of 5000 parts. When one is reassembling the chain, it is important to match the lengths of the parallel links to an accuracy of ±0.13 mm to maintain the straightness of the chain.

6.3.3 Troubleshooting Chain Charging Systems

If the charging current(s) are not stable and the external power supplies have been found to be operating correctly, then a detailed inspection of the components inside the tank is necessary. Inside the tank are usually resistors mounted onto the high voltage feedthroughs that serve to limit current from sparks that would otherwise damage the external power supplies. These can be damaged, and should be measured to verify that they are within tolerance. If they are open, the charging efficiency will be reduced considerably.

The resistance of the antistatic drive sheave should be measured between the chain pellets in contact with the rim and the metal wheel. This resistance should be low, less than 20 Ω as measured with a simple hand-held multimeter. High resistance indicates that the contact bands are misadjusted or worn to the point that they should be replaced. The chain should be inspected for evidence of wear. The rivets that attach the nylon links to the chain pellets should be inspected for fret corrosion – this typically shows up as a reddish ring around the head of the rivet. If this is found, the rivet should be removed and replaced. If this is left untouched, the corrosion will continue and worsen to the point that the rivet may come loose from the pellet and the chain may break. The idler wheels, if installed, should be checked for cleanliness and bearing integrity. Dirty idlers can cause parasitic leakage from the charging chain to the column. Typically, the problem arises from grease lost from the bearings in the idlers, signaling that the bearing is at the end of its useful life and should be replaced. In the terminal, the adjustment of the gaps between the chain and the electrodes should be checked with the standard jig supplied by the manufacturer. The standard gap is 6.35 mm. For maximum charging efficiency, the gaps of the inductor and suppressor shoes at the grounded end of the column and in the terminal must be equal to match the capacitances between these electrodes and the chain. The resistance of the charge pickoff wheel to the terminal should also be checked and should be about 1 MΩ. Any evidence of lubricant leakage from the bearings in the charge pickoff wheel also indicates the need for replacement. Typically, the bearing lifetime approaches 20 000 operating hours.

When adjusting the inductor and suppressor shoes, one should observe the chain as it leaves and arrives at the drive wheels, as the path is not horizontal owing to the momentum of the chain as it leaves the wheel. After the chain path has been observed, the chain is stopped and a correction is made to the inductor electrode to tip it such that the gap between the electrode and the moving chain is constant. This may take several iterations and should result in a slight increase in the charging efficiency. Typically, the coned end of the inductor is tipped 4 to 5 mm closer to the chain to achieve the proper running gap. In the terminal, the chain approaches the charging sheave horizontally but again, when leaving the wheel, on the run back to the base end, tends to follow the curvature of the wheel, and the larger gap needs to be compensated for as described previously.

When running, the chain should be very stable, having no bounce over the length of the run. Vertical motion in the traveling chain produces excessive loads on the idler pulley bearings and in the chain itself – resulting in drastically shorter lifetimes for the chain and other mechanical components in the system. In a Pelletron, the tension in the chain is provided by a set of lead weights applied to the pendulum arm at the grounded end of the accelerator tank. The tension is adjusted by adding or removing lead weights (approximately 5.5 kg each). The typical chain tension is ∼34 N/m of chain length.

In an FN tandem, this amounts to approximately 450 N, which requires eight to eleven lead weights to achieve. Owing to the lever arms involved, this will produce a variation in the chain tension of between 450 and 650 N.

In the terminal, the Pelletron system uses a passive system to produce the down charge, whereas the Laddertron system utilizes active power supplies to achieve down charge. Charge collection is achieved by charge pickoff wheels located ahead of the terminal drive wheel. These conductive wheels are adjusted to contact the running chain but not to support it. When running, these charge pickoff wheels should remain in continuous contact with the running chain for uniform charge collection. Excessive skipping may indicate the need to adjust the tension in the chain as previously described. If the pickoff wheels are adjusted such that they are loaded by the chain, the lifetime of the bearings in these wheels will be drastically shortened, resulting in premature failure of the charging system. These wheels are tested with the chain stationary, with a 500 V megohmmeter. A good wheel will have a resistance between 1 and 500 MΩ. Resistances larger than this indicate the need for replacement. The electrodes that surround the chain at the pickoff wheel locations are also adjusted to a nominal 6.35 mm gap.

The drive sheaves are made of conductive plastic mounted onto aluminum wheels. Some installations also include metal side bands to improve the connection to the chain. Typically, for these installations the contact-band-to-chain resistance should be under 20 Ω. The resistance of the conductive plastic wheel to the metal inner wheel should be also be no more than 500 MΩ.

Drastically reduced charging efficiency can often be traced to a failure in the high-voltage feedthroughs for the inductor and suppressor electrodes at the base of the accelerator. These feedthroughs are typically protected by a large 50 kW resistor in series with the lead between the feedthrough and the electrode. These resistors are susceptible to sparks down the chain or column, and the usual failure mode is for the resistor to open up. This results in no or an unstable voltage on the inductor or suppressor electrode. These resistors should be checked at every maintenance with a simple ohmmeter and replaced if not within ±10% of their nominal value. It is also a good idea to install a spark gap on the electrode side of these resistors to limit the overvoltage impressed on them during a spark.