Troubleshooting Concepts for Line Modulators used in Medical Linear Accelerators

This article is intended to present an open discussion on practical concepts, adjustments, and troubleshooting of line modulators used in most medical linear accelerators. It is assumed herein that the readers are familiar with the basic operation and theoretical concepts of how a line modulator works.

It is likewise assumed that you are familiar with proper safety procedures such as shorting stick procedures and disabling radiation while troubleshooting in the treatment room. If you have not been trained in the proper safety procedures for troubleshooting and maintaining linear accelerators, or if you are not sure how to do any of the steps or procedures indicated below, please seek competent assistance and do not attempt any procedures that you are not completely competent to safely perform.

Most of my experience in troubleshooting these systems has been with Siemens and Varian medical accelerators; however, a great portion of the material presented here could be applicable to other systems. The concepts presented here come from many sources and many colleagues who very kindly shared their knowledge with me. I therefore take no credit and thank those folks who taught me.

Most medical accelerator systems use a line modulator with a resonant charging system. A line modulator consists of a *pulse forming network* *(PFN)* which works like a constant transmission line. The resonant charging system is used to charge the PFN to a programed level. This energy, or charge, will then be discharged into a load.

So, it is very helpful to break the modulator into two sections:

a) a charging system which stores energy in the PFN, and
b) a discharge system composed of a discharge device and a load

Charging system

This is nothing more than a resonant LC circuit. The L (inductor) is the ***charging choke*** and the C (capacitance) is the total capacitance of the 6 or 7 **PFN capacitors.** The period of the charging cycle waveform is a function of the values of L and C. The corresponding waveform for a Varian accelerator is "HVPS-I" while for a Siemens accelerator, it is "Charge I"**. So if the "*full charge period*" in this signal changes, it means that either L or C have changed values.** It has been my experience that in most cases, the culprit has been the charging choke. And the best way to diagnose it is by substitution. Capacitors do also fail, but it is less frequent.

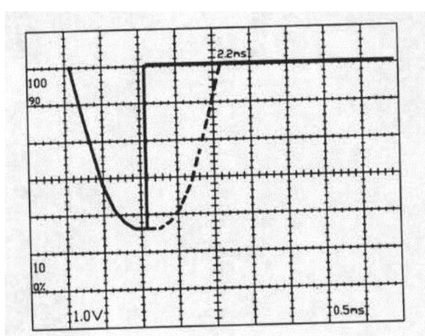


Figure 1.
Charging current for a Klystron Modulator. The waveform obtained is only half a period. L=3.3 H & C =0.21microF

Charging choke Failures:

The choke, combined with the steering diodes, also serves to isolate the HV power supply from the rest of the modulator, including the main thyratron while the latter is conducting. The choke basically prevents a dead short from the HVPS output to ground through the main thyratron, which would otherwise result in an HVOC interlock and most probably in an HVPS circuit breaker trip. This type of failure usually occurs when the choke windings arc through the choke's insulation or if one or more of the turns in the choke are shorted. Shorted turns effectively reduce the Q factor of the inductor, thus eliminating its ability to isolate.

In the case of an arcing choke, one usually is able to see marks on the choke. Turning lights off and watching while pulsing also will reveal the problem. Problems with reduction of Q factor in the choke are very difficult to troubleshoot. Usually, the breaker trips before one has time to view any of the waveforms, though you may see something if you set your scope up for a single sweep trigger. Also, testing the choke with meters statically does not yield conclusive results. Once again, substitution is the best way to rule out a choke with shorted turns.

PFN Capacitors:

PFN capacitors are usually easier to diagnose. If one capacitor is defective or if it opens, one would see a gap and/or a pulse width decrease in Pulse I (Varian: Klystron Current -KLY I, or Magnetron Current -Mag I). Usually there is also physical evidence; such as swelling of the capacitors casing or oil leaking out of the case. If one is able to pulse the system, one would also note a decrease in the HVPS I (or Charge I) charging period due to the decrease in the capacitance value.

Diodes:

Shorted diodes on the charge side of the modulator are other possible causes for HVPS Overcurrent (HVOC) interlocks. I have seeing them change the shape (not the period) of the HVPS I (or Charge I) pulse. Sometimes there is physical evidence of damage (heat) in the diode. I have seen diodes in the HV power supply go bad, but never a charging diode. A good way to test HV diodes statically is to connect a 50 ohm resistor in series with the diode and supply 18 Vdc with two 9V batteries. One should be able to measure the Knee voltage with a voltmeter, 7.5 Volts or 5.5 volts, depending on the diode, with it connected in forward bias. Reversing the polarity of the 18V would have the diode behave as an open circuit. If you find a defective diode, remember to always change all diodes in the stack. Never change just one diode.

Discharge system - PFN discharge into a load:

The PFN capacitors together with the PFN inductors are modeled after a transmission line, such as a long coax cable. The capacitance between its center conductor and the outer shield is simulated by the PFN capacitors and the PFN inductors represent the inductance in the coax as a function of length. Now, one might ask, why are these coils not considered when analyzing the charge period? The inductance of these coils is very small compared to the inductance of the choke, so their contribution to the charging period is negligible. On the other hand, the combined inductance of the PFN coils is quite significant in the much faster discharge circuit. Also, the value of each individual inductor section in the PFN can be adjusted by adding or removing turns. By doing this, one is actually able to change the shape of Pulse I (KLY I/Mag I) and maximize/optimize Target I (Beam output per pulse). We shall cover this in another article.

The energy stored after each charge cycle is to be discharged at the appropriate time into a load. In our case, the load consists of Pulse cables, a Pulse transformer, a de-spiking network, and a Magnetron or Klystron. As with any transmission line, **the impedance of our load must be equal to the PFN output impedance for 100% of the energy**

stored in the PFN to transfer to our load. If there is a positive impedance mismatch between the two sides (Load impedance > source impedance), an incomplete energy transfer to the load occurs (an incomplete discharge of the PFN) and some of the energy remains in the reactive elements of the PFN. If a negative mismatch occurs (Load impedance < source impedance), the PFN discharge could overshoot, charging the PFN to a negative value. If this mismatch and resulting overshoot is severe enough, it will trip the MOD interlock. (We will discuss more on the MOD I/L later.) In our case, the load impedance is designed to be slightly less than the PFN output impedance. This small mismatch results in a small overshoot, leaving some energy remaining in the PFN as a negative voltage. (Notice that your PFN V waveform always goes a little negative.) Why? This ensures that the main thyratron is turned off (anode has negative voltage) after the discharge cycle is completed. If the thyratron is not turned off, it will be conducting when the next charging cycle begins. And once the choke saturates, current will flow from the power supply through the choke and then through the main thyratron to ground, tripping the HVOC interlock and most probably tripping the HVPS CB.

In most cases an HVOC interlock indicates a problem with the charging portion of our system. . However, I know of two cases where a faulty magnetron caused such a positive mismatch that the (positive) charge remaining in the PFN caused the Main Thyratron to remain on, crowbarring the charge cycle and produce an HVOC interlock as described above. These are the only times I have seen a faulty load produce an HVOC interlock.

Other known causes for a Main Thyratron crowbarring:

1. Improper thyratron filament or Reservoir voltage
2. Defective thyratron (Most probable cause)
3. Defective pulse transformer

MOD / Clipper Interlock:

If the load impedance is much less than the source, the negative charge in the PFN might damage some components. For example, it might exceed the specs for reverse voltage of the main thyratron . To prevent damage in this situation; a circuit called the CLIPPER, or End Clipper, is used. It is basically an MOV (varistor), a diode conducting in the negative direction and a resistor in series. If the negative voltage spike exceeds a certain limit (about 2KV for Siemens and 5KV for Varian), the MOV breaks down to roughly zero ohms and shunts the excess negative charge to ground via the diode and resistor. The current of this circuit is sampled (with a toroid on Varian linacs) and if it exceeds a threshold, the modulator is disabled with a MOD (Varian), or CLIPPER (Siemens) Interlock.

Figure 2 depicts both a normal condition with proper impedance mismatch, as well as a large impedance mismatch cause by a load arc

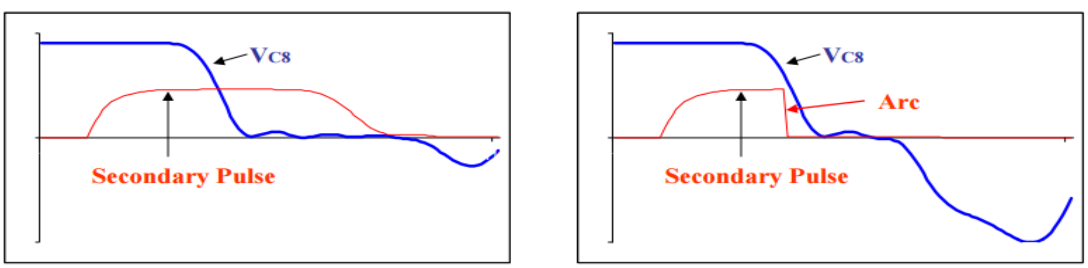


Figure 2: On the left (normal Operation), the voltage across the last PFN capacitor holds its charge during the first half of Pulse I (Secondary Pulse) duration. After the pulse, a small portion of the energy comes back and charges the PFN

capacitors with a negative voltage. On the right side, an arc in the load causes a large impedance mismatch, resulting in a much higher negative charge in the PFN capacitors. Source: The Linac Modulator.

DeQueing circuit:

The Dequeing circuit controls the amount of charge stored in the PFN during the charging cycle. Regulation is accomplished by drastically decreasing the Q factor of the choke when the desired, or programed, PFN charge level is reached. This is accomplished by firing a tube (DeQueing thyratron) which shunts high power resistors across the choke. When the De Queing thyratron conducts, all of the remaining energy stored in the choke is dissipated through the shunt resistors, drastically reducing the its Q factor and stopping the flow of current to the PFN. A non-functioning DeQueing thyratron will allow the PFN to overcharge which, in turn, will often cause a Magnetron or Klystron to arc. This results in Mod (Clipper) Interlocks. There are many other possibilities. For instance, a DeQueing thyratron fires prematurely at any point above the 11-13KV level (but below the programmed level) may cause low or no output because it prevents the PFN from reaching the programmed value. Most problems with the DeQueing circuit are caused by a faulty DeQueing thyratron. Though on one occasion, I encountered an open shunt resistor.

Additional troubleshooting tips:

Troubleshooting the modulator is a difficult task. Usually, the fault will trip interlocks too soon, making troubleshooting and monitoring signals very difficult at times. When working on the modulator, the most important thing to remember is SAFETY. I'd like to reiterate that you should not attempt any of the following steps if you have not received the proper training for operating and troubleshooting linear accelerators and modulators.

These are general guidelines and tips. Detailed methods would depend on the specific manufacturer and model of your system.

1. Before touching anything in the modulator HV area, discharge the modulator with the hook stick.
2. Check connections for integrity and tightness. I have solved about 15% of strange problems just doing this.
3. Check equipment grounds, and make sure that the Facility isolation transformer is "still" well grounded.

HV CB trips and/or HVOC/HVPS over current interlock:

1. Check filament and Res voltage at main thyratron.
2. Disconnect Main thyratron and turn Beam on. Does the breaker trip?
3. Replace main thyratron.
4. Check connections as described above.
5. Check PFN caps for physical evidence of failure
6. Check charging choke for physical evidence of arcing
7. Decrease PFN program voltage to lower Pulse I (Kly I/Mag I), reduce PRF (for discrete PRF systems, choose an energy with lowest PRF). This might allow one to run system long enough to troubleshoot it.
8. If HVPS I (Charge I) period is different, see if Pulse I (Kly I/Mag I) presents a notch. If it doesn't replace the choke. If a notch is present in Pulse I consider replacing the PFN capacitors.
9. Check HV diodes, including the rectifiers in the HV PS.
10. Check if clipper diode is shorted.
11. Very unlikely the problem will be in the load, but monitor PFN-E (PFN V) and make sure that the signal goes a little negative after discharging. Compare with an earlier picture. Remember, if there is not enough negative voltage at the Anode of the main thyratron, the tube might crowbar.
12. If you would like to completely rule out the load, use a dummy load if available. Some designs allow disconnecting the load and using existing elements as dummy loads for a short pulsing time.

Clipper or Mod interlock:

1. This interlock indicates a problem with your load.
2. If you have dummy loads, use them to isolate the problem (pulse tank or magnetron???)
3. It is known that Varian HE systems may be pulsed with three Pulse cables instead of four. Do this until you rule out all four cables. Remember to disconnect both ends of each cable, one at a time, until you find the faulty cable, and do not run with less than 3 cables connected.
4. In Varian HE linacs, to eliminate Pulse cables, Pulse Thank and Klystron, disconnect all four pulse cables at the modulator end. Jumper out capacitor in the de-spiking circuit and use this circuit as a load. Pulse for a short time to see if the breaker or interlock trips.
5. Check basics. On LE Varian linacs, make sure that the magnetron filament is 8.5VDC when the modulator is not being pulsed and verify proper operation of the cutback circuit.

Unstable Pulse I (Kly I/Mag I):

1. Monitor PFN -E (PFN V) and Charge I (HVPS I). Do they look the same as per a good parameter sheet? Is PFN-E stable and of constant amplitude? If so, the problem is in your load.
2. This works well for magnetron systems. Disconnect one or two PFN caps. Pulse the system. If Pulse I is more stable, then the problem is more likely to be your magnetron (i.e. the pulse tank is more sensitive to the amount of work done or average power than the magnetron).
3. Check the PFN voltage divider used to sample PFN E (PFN V)
4. Check your reference PFN voltage. Is it constant?

Magnetron internal arcing:
One can process (“clean” or “outgas”) and arcing magnetron. To do so:

1. Lower PFN-Program voltage as much as possible
2. Lower PRF as much as possible
3. Pulse the modulator and manually sweep the magnetron frequency.
4. If you see arcing in the scope, stop sweeping the frequency and let it arc until it stops.
5. Increase Pulse I amplitude and repeat the process. If the Modulator trips, then lower PFN program voltage.
6. The idea is to get the modulator running with Pulse I (Mag I) at about 100 - 105 amps and then increase the PRF. Some systems allow for continuous control of PRF, some others do not.
7. This process might not succeed in getting the magnetron to stop arcing. In this case, the magnetron should be replaced.

In some cases, the arcs observed while monitoring Pulse I are caused by the pulse thank.

1. On older Siemens systems, this is usually due to air trapped inside the pulse tank. One must purge the air out of the pulse tank.
2. If outgassing the magnetron does not work. The only way to be certain as of which of the two is the culprit is two either replace one of the two, or use a dummy load for the magnetron. I must say that in my experience, the culprit is usually the magnetron.

Final Notes

Again, there is one thing I would like to stress to engineers, especially those who are beginning, and that is SAFETY. Take your time. Get in the habit of discharging the PFN every time you are going to work in the HV area. Wear rubber sole shoes. Do not work alone with difficult HV problems. I was once saved by an observant less experienced colleague.

Once again, this article is based on my experience with Varian and Siemens medical linacs. Comments on other brands are more than welcome.

I you would like to comment, correct or add to the contents presented here, please do so. Our goal is precisely to start a good discussion for

everyone's benefit.

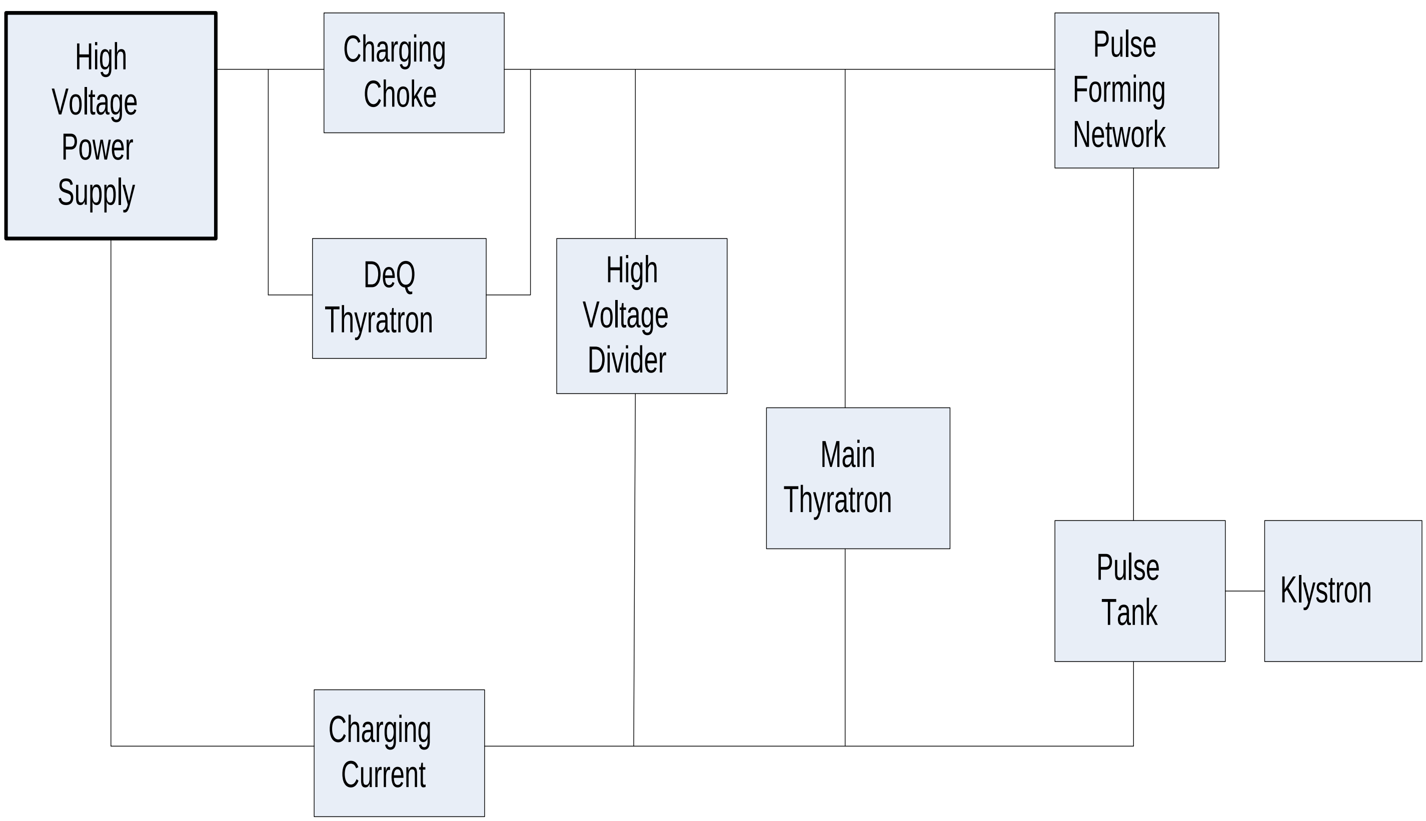
Finally, I would like to thank Dave Sauter for providing the block diagrams for the appendix, as well as Ken Wright for a fantastic editing job.

Thank you

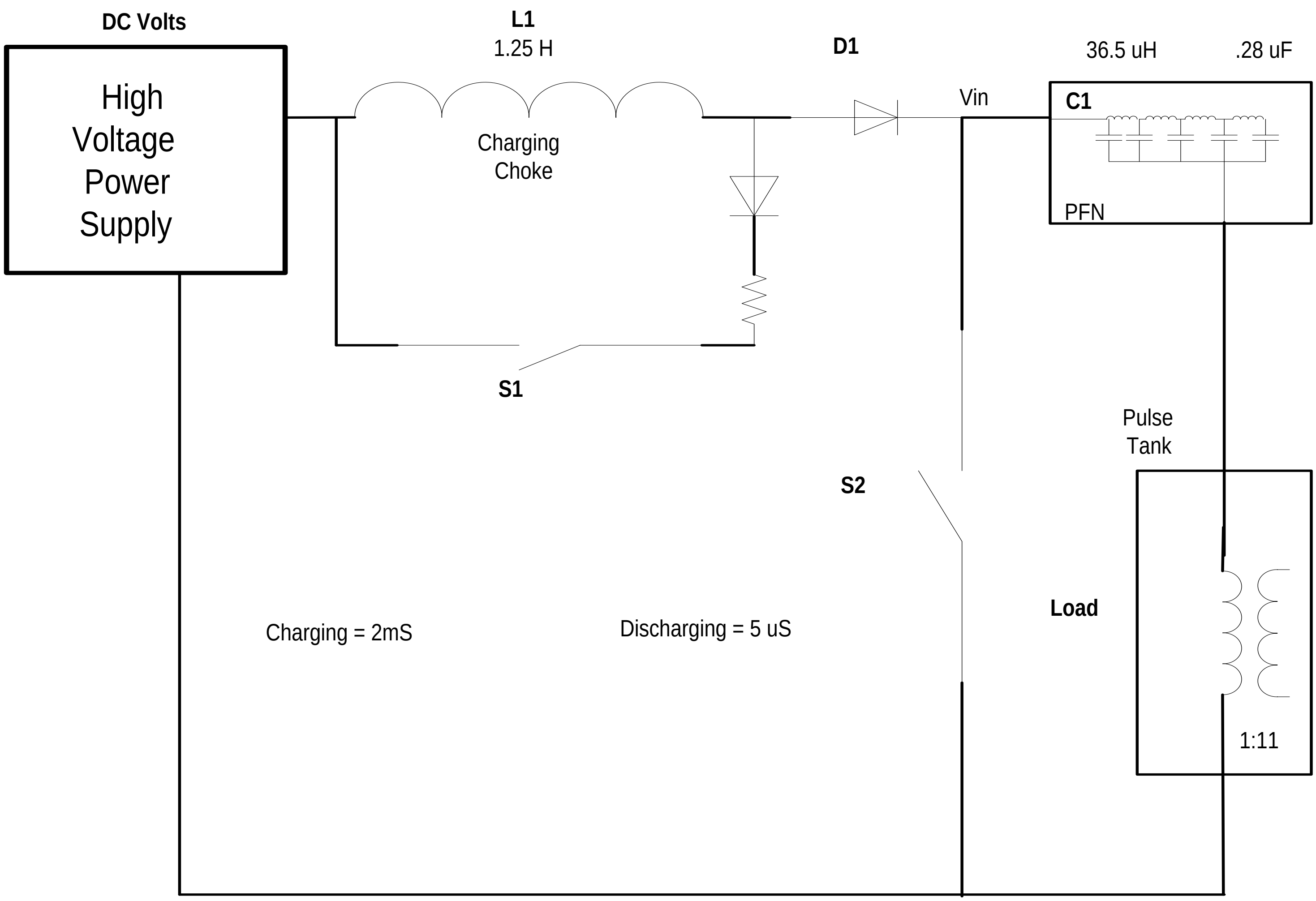
Luis Segovia
Just another linac guy.

Appendix Simplified modulator circuit diagram

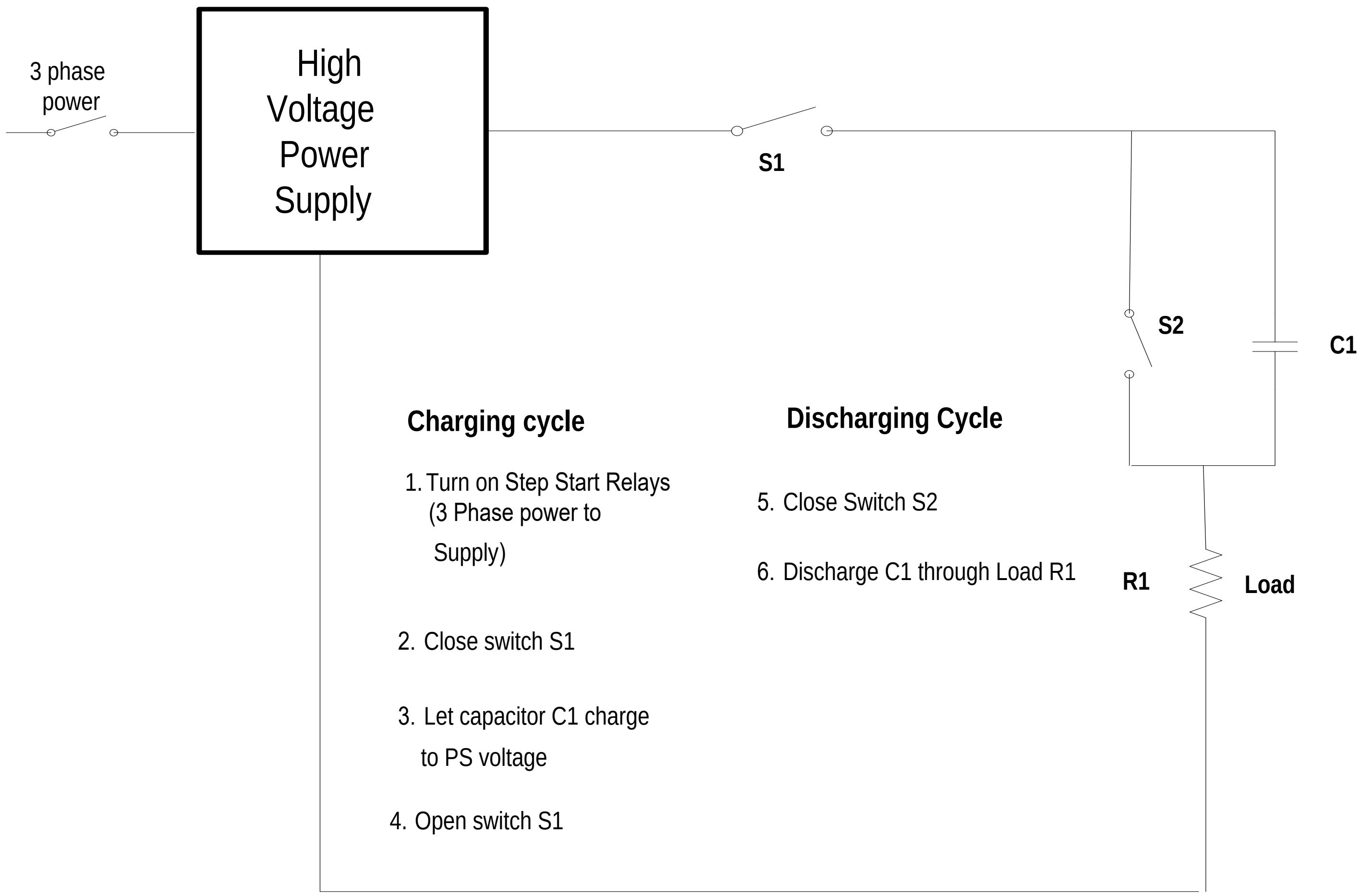
Modulator; Block Diagram



Modulator simplified diagram with switches

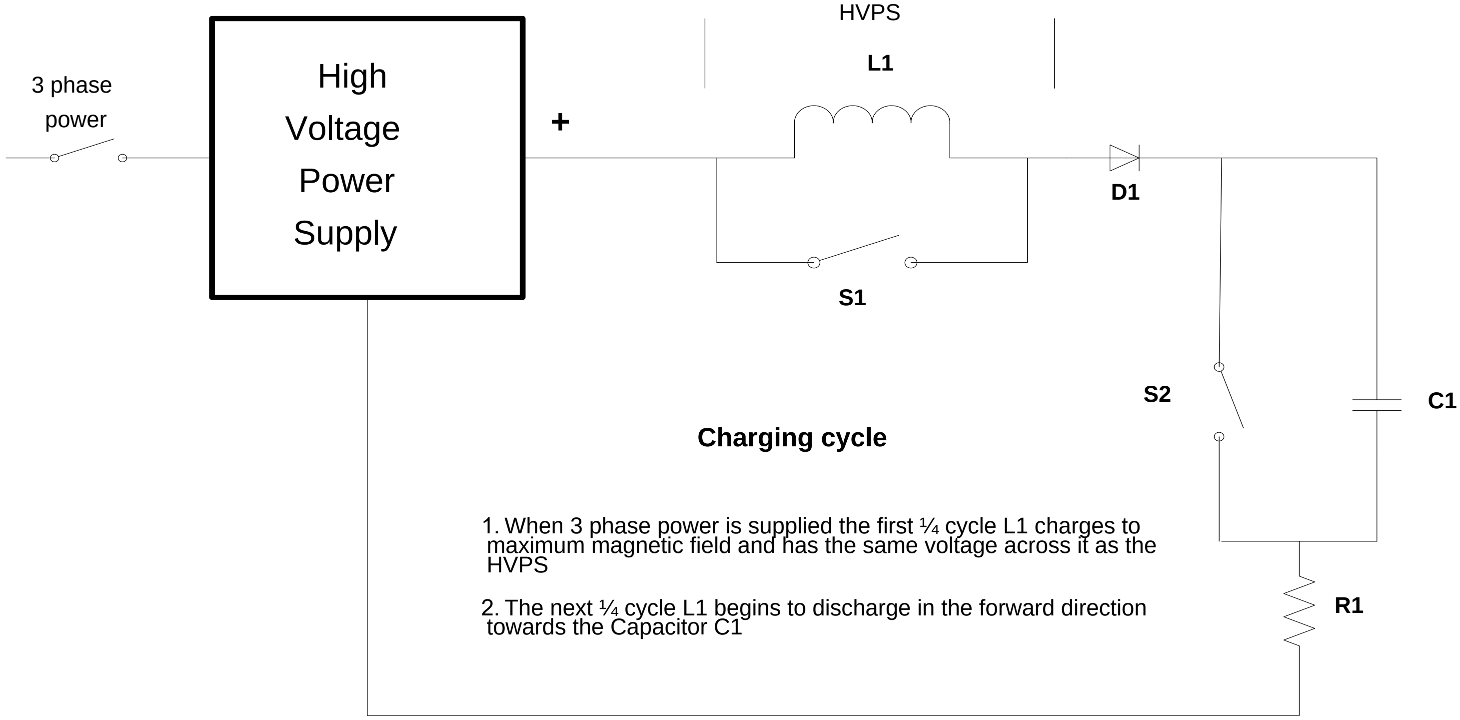


Basic Modulator



Base Modulator

This diagram has the same components as the first diagram with 2 more components added; L1 and D1 to circuit



Charging cycle

1. When 3 phase power is supplied the first ¼ cycle L1 charges to maximum magnetic field and has the same voltage across it as the HVPS

2. The next ¼ cycle L1 begins to discharge in the forward direction towards the Capacitor C1

3. The resultant is C1 can charge up to 2x HVPS when L1 has reduced its magnetic field to zero by the end of this second ¼ cycle

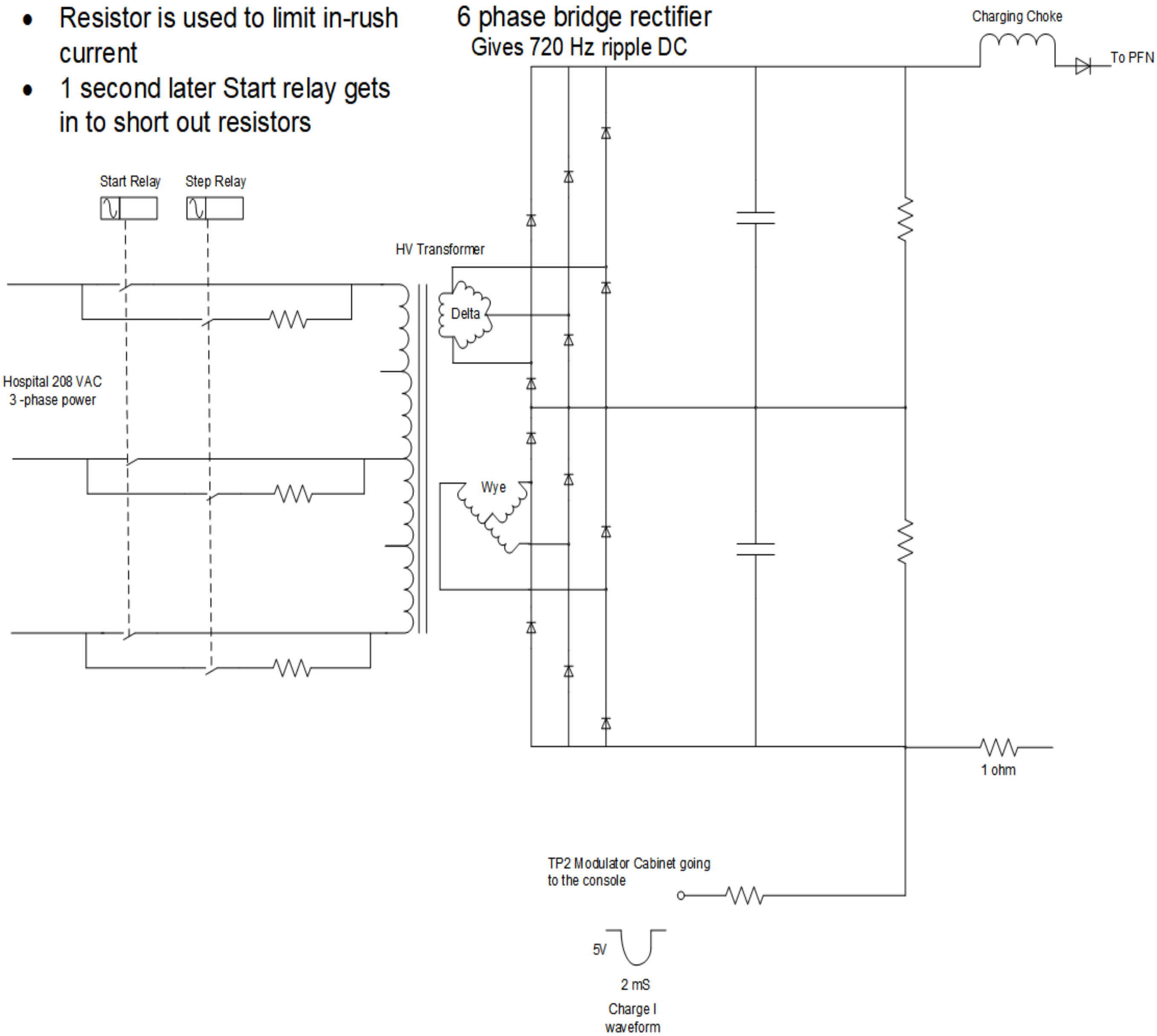
4. S1 is used to stop the charging of C1 before it gets to 2x HVPS

5. D1 is used so C1 cannot discharge back through L1

6. Discharging cycle operates the same as in the previous diagram

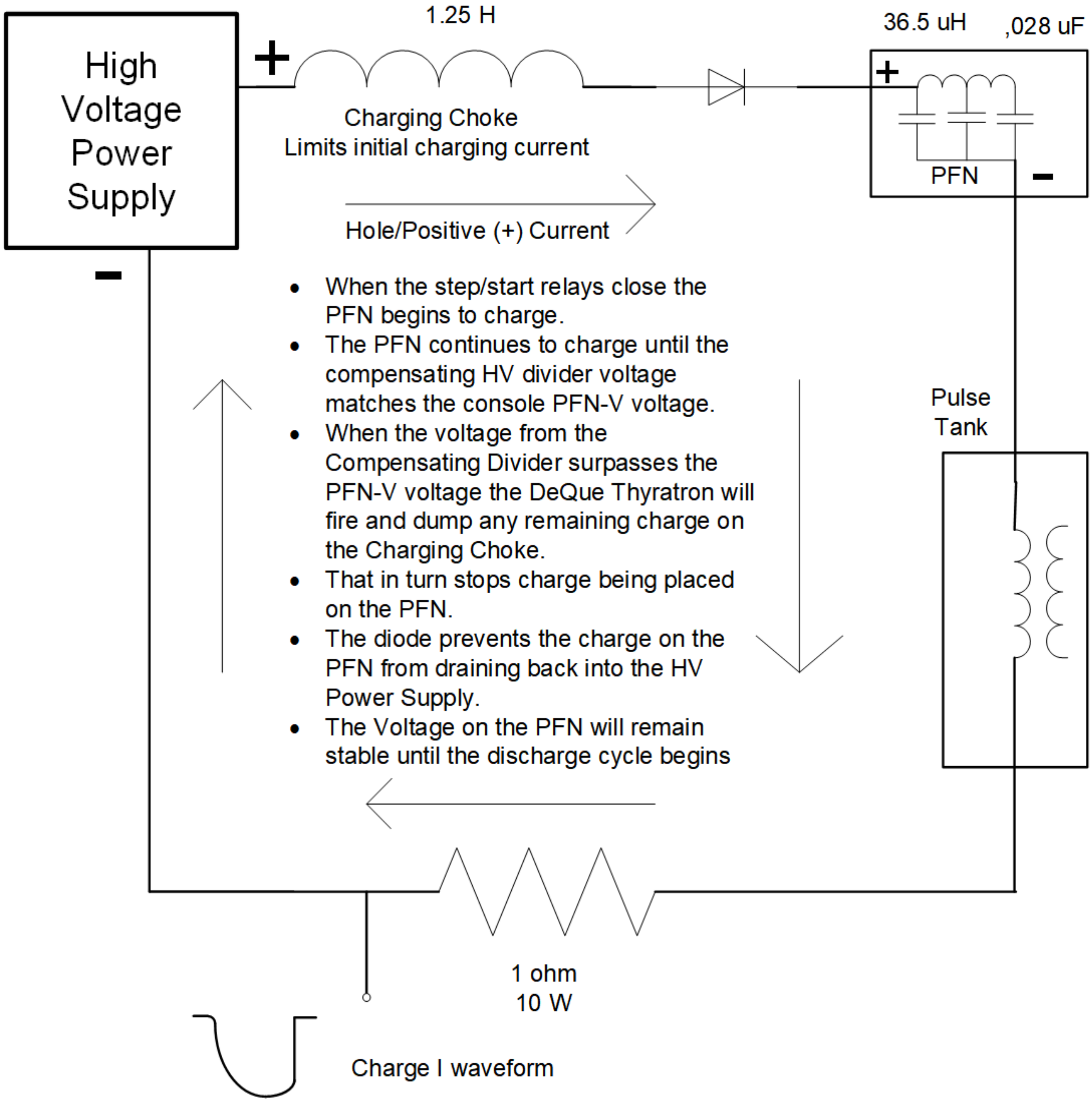
High Voltage Power Supply in Modulator

- Step relay gets in
- Resistor is used to limit in-rush current
- 1 second later Start relay gets in to short out resistors



- The HVPS changes the 3 phase AC from the hospital into roughly (750 Hz ripple) DC power

Charging Cycle (approx 2 mS)

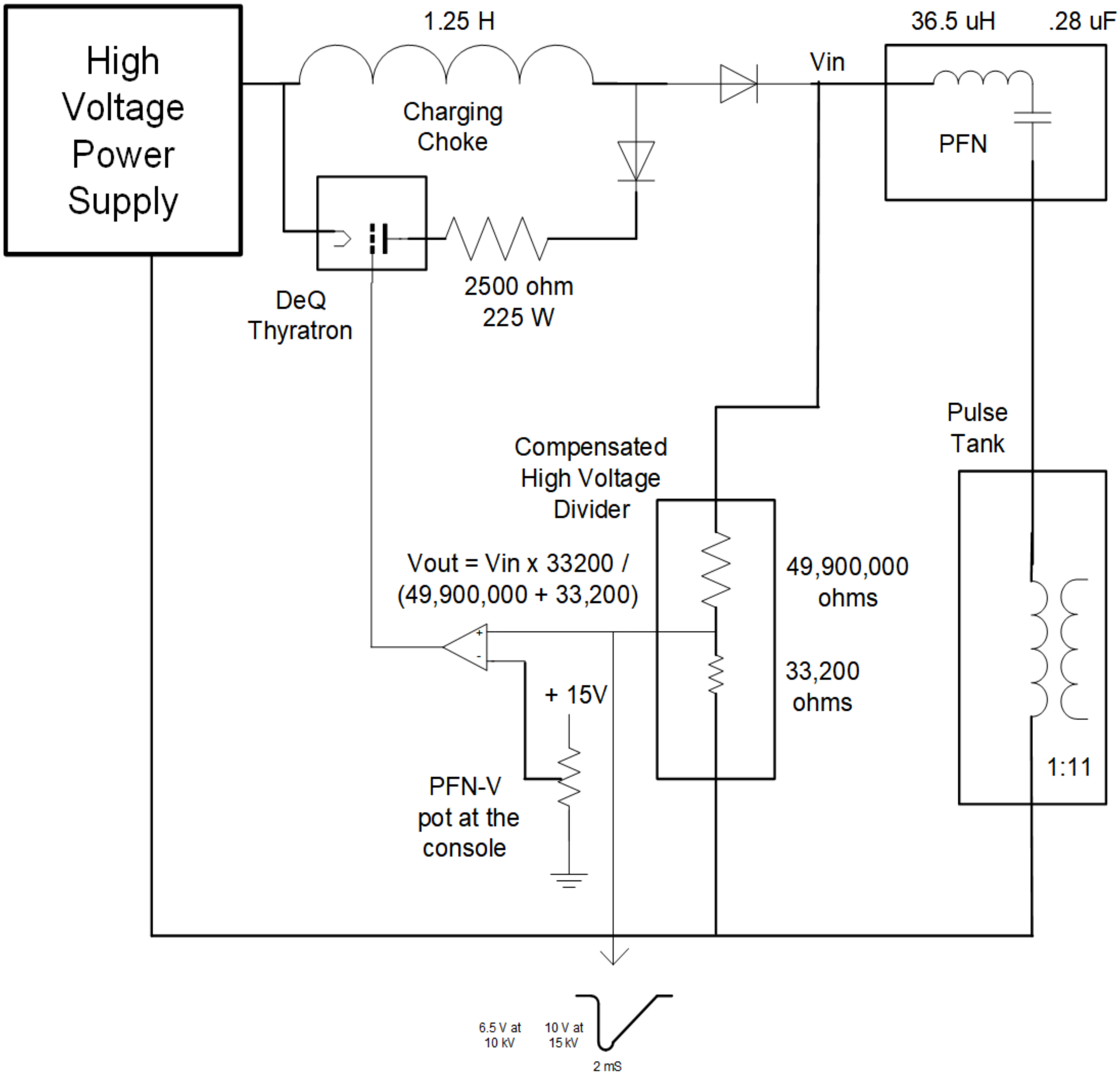


- When the step/start relays close the PFN begins to charge.
- The PFN continues to charge until the compensating HV divider voltage matches the console PFN-V voltage.
- When the voltage from the Compensating Divider surpasses the PFN-V voltage the DeQue Thyratron will fire and dump any remaining charge on the Charging Choke.
- That in turn stops charge being placed on the PFN.
- The diode prevents the charge on the PFN from draining back into the HV Power Supply.
- The Voltage on the PFN will remain stable until the discharge cycle begins

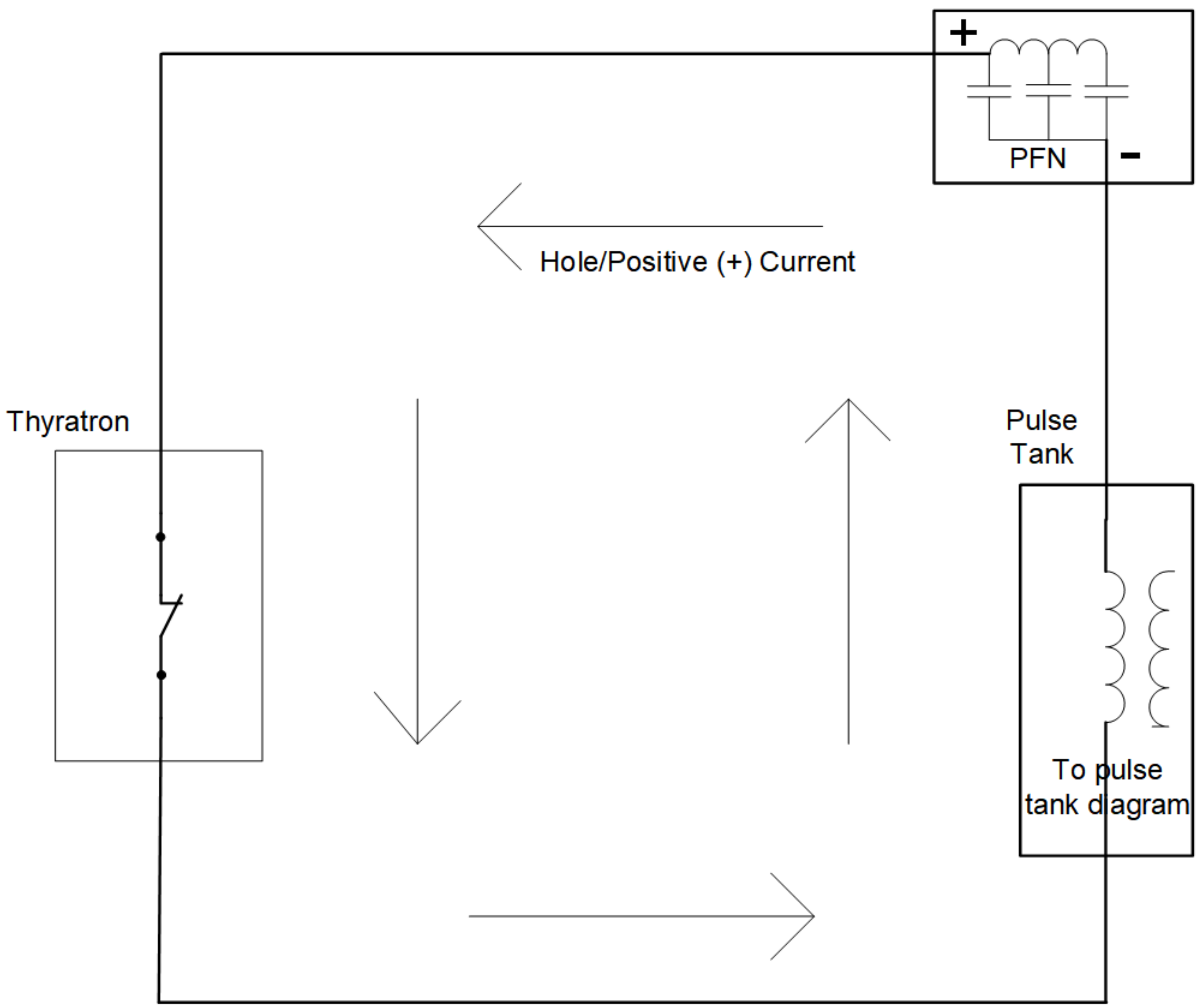
Charging circuit

Q proportional to L / R

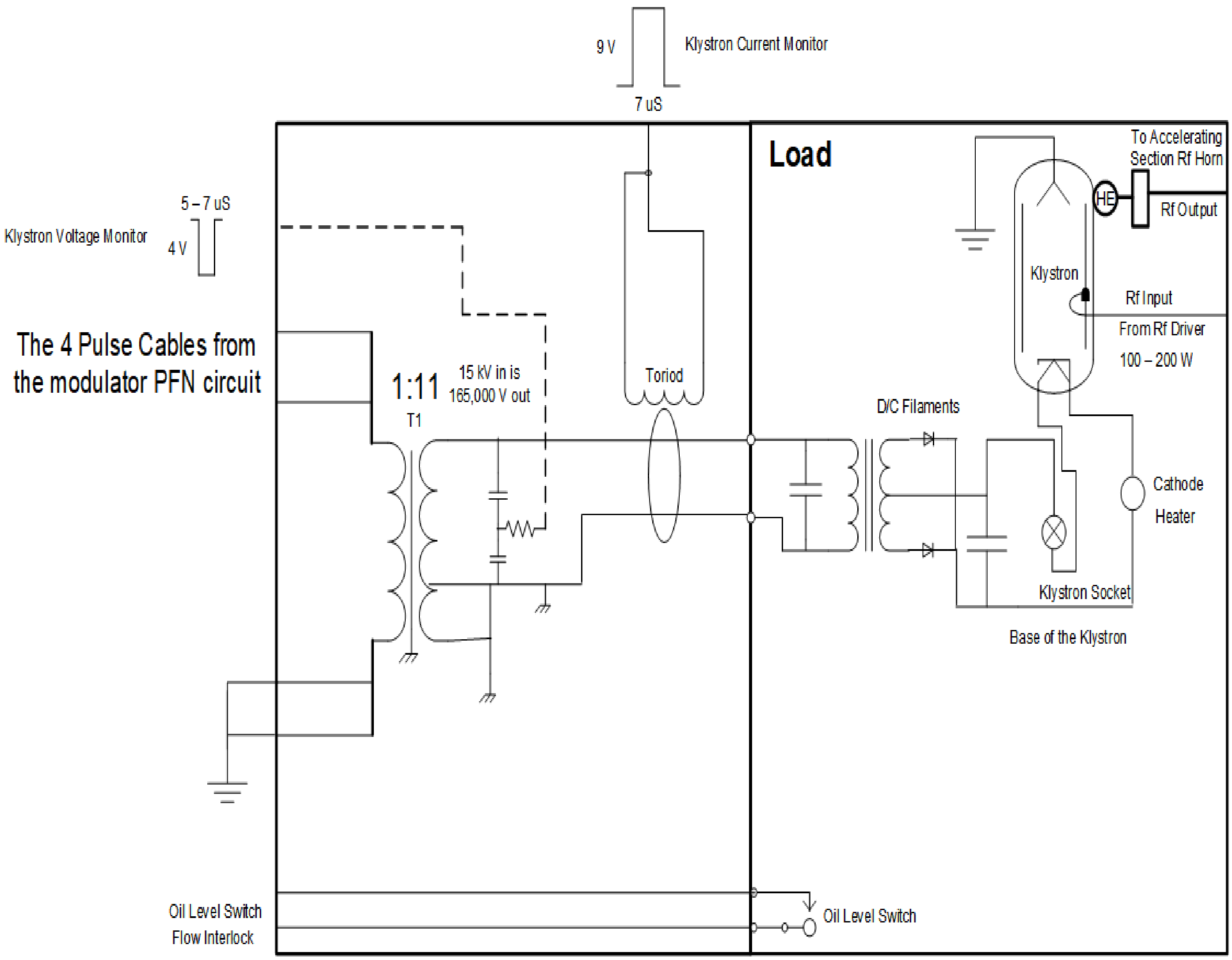
- DeQue Circuit; where:
- Q =wL/R
- Q being proportional to L/R
- w = 2 x Pi x f



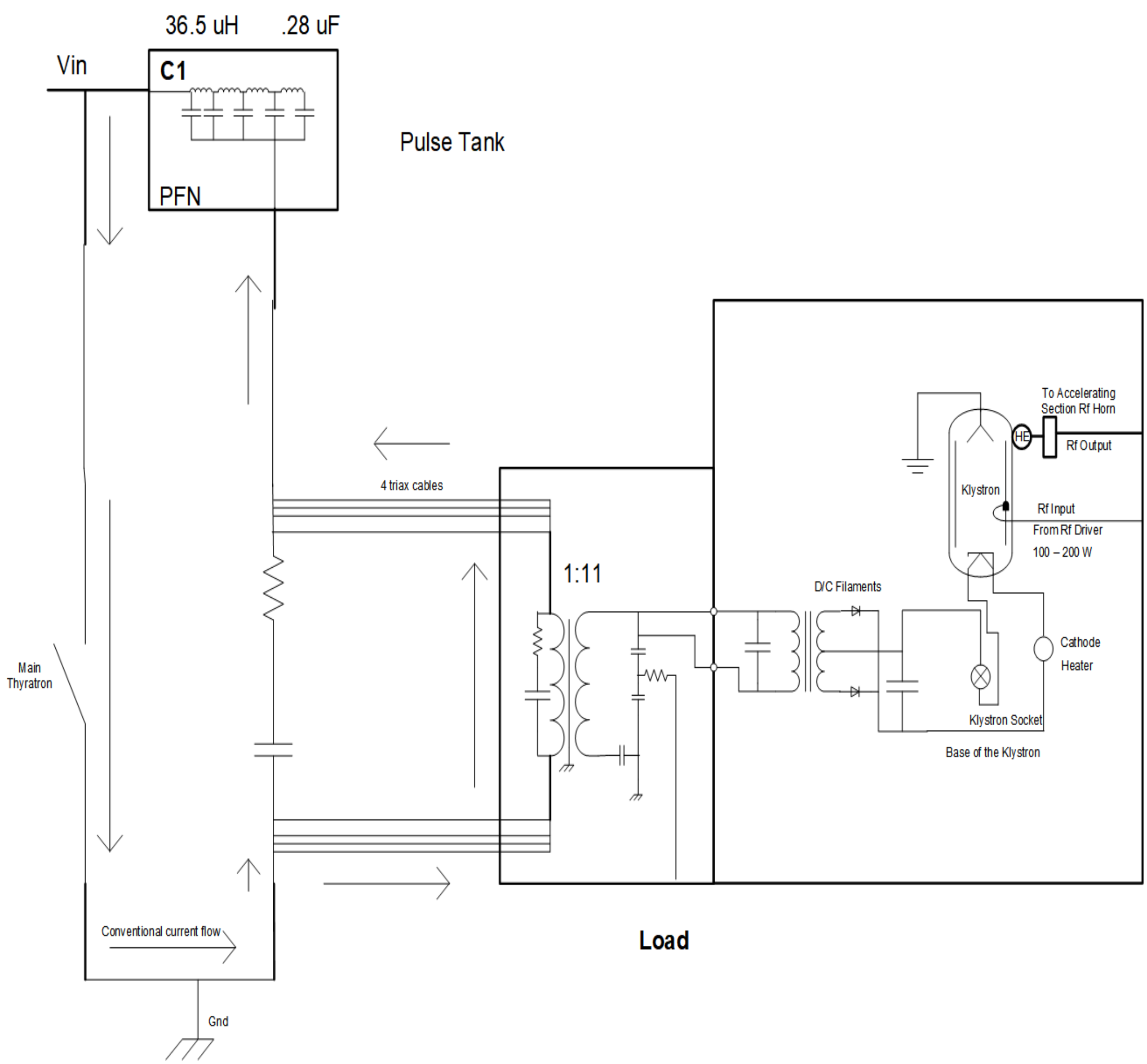
Modulator Discharge Cycle
(approx 5 uS)



Pulse Tank Diagram



Discharge Cycle



Load