Introduction to High and Low Voltage Power Supplies

The definition of high and low voltages is not univocal, and the usage of these expressions in the research community and in the electro technical industry may differ significantly.

The International Electrotechnical Commission and its national counterparts (IEE in the UK, VDE in Germany, etc.) classify high and low voltage circuits as follows:

	AC	DC
High Voltage (HV)	> 1000 V	> 1500 V
Low Voltage (LV)	50 – 1000 V	120 – 1500V
Extra Low Voltage (ELV)	< 50 V	< 120 V
Safety ELV (SELV)	25V	60V

In the United States 2005 National Electrical Code (NEC), high voltage is any voltage over 600 V (article 490.2).

In the scientific community and in the spin-off industry the difference between low and high voltage is sometimes related to the application.

For example, "high voltage" is used in many particle detectors to create an electric field that allows to amplify particle signals and therefore to detect particles. Therefore, a high voltage unit could be the 3kV power supply for a photomultiplier as well as the high precision 100V power supply for the bias of a semiconductor detector. On the other hand, low voltage is used to feed the analog and digital electronics integrated in the detectors or into other applications.

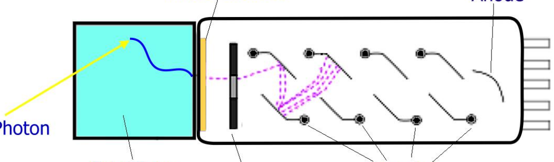
All Wiener power supplies are DC power supplies with the following properties:

- Modular design
- High degree of reliability
- Robust construction
- Sophisticated hardware protection against over currents, over/under voltage, shorts
- Availability of remote controlling and monitoring

Power Supplies for Particle Detection

Photomultiplier

Photomultiplier tubes (PMT's) are extremely sensitive detectors of light in the ultraviolet, visible and near infrared spectrum. Using the photoelectric effect, electrons are produced which are then multiplied in the electric field of electrodes (dynodes) with increasing high voltage. The signal is taken off the Anode. PMT's multiply the signal produced by incident light by as much as 10^8, allowing single photon detection.



Scintillating detector with Photomultiplier

PMT's typically require 1000V to 3000V operation voltage for proper operation. Negative high voltage supplies are usually preferred. The high voltages are divided and distributed to the dynodes by a passive resistive or active voltage divider in the PMT socket.

While powered, photomultipliers must be shielded from ambient light to prevent their destruction through over excitation.

In case used in a location with magnetic fields PMT's have to be shielded by a layer of mu-metal (nickel-iron alloy with very high μ, i.e. magnetic permeability).

PMT Power Supply Requirements	
Typical Voltage	1 – 3 kV
Typical Current	0.1 …3mA
Polarity	Positive or Negative (common)

Photodiode

A photodiode is a semiconductor diode that functions as a photo detector. When light of sufficient photon energy strikes the diode, it excites an electron thereby creating a mobile electron and a positively charged electron hole. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in field of the depletion region, producing a photocurrent.

In zero bias mode, light falling on the diode causes a current across the device, leading to forward bias which in turn induces "dark current" in the opposite direction to the photocurrent. This is called the photovoltaic effect, and is the basis for solar cells.

Reverse bias induces only little currents (known as saturation or back currents) along its direction. But a more important effect of reverse bias is widening of the depletion layer (Therefore expanding the reaction volume) and strengthening the photocurrent. Circuits based on this effect are more sensitive to light than ones based on the photovoltaic effect.

Photo Diode Power Supply Requirements	
Typical Voltage	5V to 100V
Typical Current	1 uA to 10 mA
Polarity	Positive or Negative

Avalanche Photodiode

Avalanche photodiodes (APDs) are photo detectors with high internal gain, a semiconductor analog to photomultipliers. By applying a reverse bias voltage (typically 100-200 V in silicon), APDs show an internal current gain effect (typically around 100) due to impact ionization. Some silicon APDs employ alternative doping and beveling techniques that allow greater voltage to be applied (> 1500 V) before breakdown is reached and hence a greater operating gain (> 1000). In general, the higher the reverse voltage the higher the gain.
Since APD gain varies strongly with the applied reverse bias and temperature, the reverse voltage should be stable and monitored in order to keep a stable gain. Power supplies with high monitoring and setting resolution are often necessary,.
If very high gain is needed (10^5 to 10^6), certain APDs can be operated with a reverse voltage above the APDs breakdown voltage. In this case, the APD needs to have its signal current limited and quickly diminished, for example through active or passive current quenching. APDs in high-gain regime operate in Geiger mode. This mode is particularly useful for single photon detection provided that the dark count event rate is sufficiently low.

APD Power Supply Requirements	
Typical Voltage	50 – 2000 V
Typical Current (Anode)	1 – 10 mA
Polarity	Positive or Negative

Silicon PMT

Silicon photomultipliers are new, semiconductor photon sensitive devices build from an avalanche photodiode matrix on common silicium substrate.

The dimension of each single APD micro-cell can vary from 20 to 100 microns with a possible density of up to 1000 per mm^2. Every micro-cell APD operates in Geiger mode and is decoupled from the others by a polysilicon quenching resistor. A parallel readout of all micro-cells results in a large dynamic range from a single photon up to 1000 photons per mm^2. The supply voltage depends on junction type and varies from a minimum of about 30V up to 70V.

The total quantum efficiency of 20% as well as the gain of about 10^6 are very similar to a traditional PMT's, however the G/V curve is linear and not exponential like for a PMT. Silicon PMT's have a fast time response of about 100ps for single photo electron. The small, light and compact design as well as it's independence of magnetic fields is a big advantage for detector applications.

Silicon PMT Power Supply Requirements	
Typical Voltage	25V to 70V
Typical Current	10 to 30 mA
Typical Voltage (electronics)	5V
Typical Current (electronics)	40 to 100 mA
Polarity	Positive or Negative

Silicon Strips and Silicon Pixel Detector

With semiconductor detectors it is also possible to detect charged particles. Narrow (usually around 100 micrometres wide) strips of doped silicon work as diodes, which can be reverse biased in order to enlarge the depletion zone and therefore achieve a higher sensitivity. The thicker the strip is, the higher is the bias voltage required to obtain full depletion. As charged particles pass through these strips, they cause small ionization currents which can be detected and measured. Arranging thousands of these detectors around a collision point in a particle accelerator can give an accurate picture of what paths particles take. Silicon detectors have a much higher resolution in tracking charged particles than older technologies such as cloud chambers or wire chambers. The drawback is that silicon detectors are much more expensive than these older technologies and require sophisticated cooling to reduce leakage currents (noise source) as well as suffer degradation over time from radiation.

Silicon micro-strip detectors frequently operate in high radiation environments and require a bias voltage which should be adjustable on a wide range, typically from 0 to 500V, with a remote monitoring and controlling system for voltages and currents, in order to guarantee a constant gain over time.

High precision is also required as current trips should be set for each channel and range from some nA up to some uA and calibration procedures must be executed with high accuracy in order to avoid breakdown.

Si Detectors Power Supply Requirements	
Typical Voltage (bias)	50 – 500 V
Typical Current (bias)	1 mA
Typical Voltage (electronics)	2 – 5V
Typical Current (electronics)	40 to 500 mA
Polarity	Positive or Negative

Germanium detector

Germanium detectors are mostly used for detecting gammas, especially for spectroscopy in nuclear physics. While silicon detectors cannot be thicker than a few millimiters, germanium can have a depleted, sensitive thickness of centimeters, and therefore can be used as a total absorption detector for gamma rays up to few MeV.

An accurate calibration procedures is necessary.

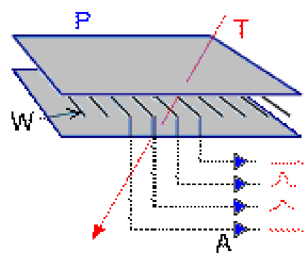
Ge Detectors Power Supply Requirements	
Typical Voltage (bias)	Up to 4500 V
Typical Current (bias)	0,1 – 1 mA
Typical Voltage (electronics)	2 – 5V
Typical Current (electronics)	40 to 500 mA
Polarity	Positive or Negative

Wire Chambers

A wire chamber is a detector for particles of ionizing radiation which constitutes a further development of the Geiger counter and of the proportional counter.

A wire carrying a high voltage passes through a metal tube or cavity whose walls are held at ground potential. Any ionizing particle that passes through the tube causes a current to flow. This allows the experimenter to count particles and, in the case of proportional counter operation mode, to determine their energy. Further developments of the wire chambers are drift chambers and time projection chambers, where the timing of the currents are used to infer the minimum distance of the particle trajectory from the wire.

Modern wire chamber need a wide range of voltages: 0,5 to 10 kV for the high voltage wires, and 0 to 1 kV for monitoring the gas purity and the conditions of the electrodes. This monitoring is very important for maintaining a high efficiency throughout the operation, where the chamber is exposed to high beam intensity. This monitoring typically involves running voltage plateau curves in many voltage steps, and an accuracy of 0,5 V is often necessary.

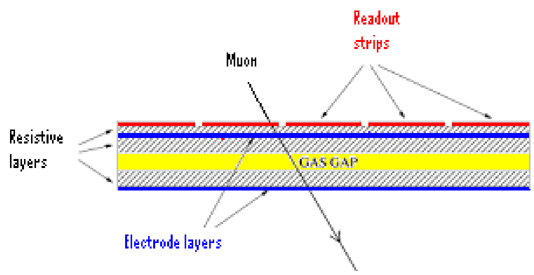


Wire chamber with cathod plates (P), wires (W), preamp (A) and crossing particle (T)

Wire Chambers Power Supply Requirements	
Typical Voltage	0,5 – 10 kV
Typical Current	1 – 30 mA/ch
Polarity	Positive (common) or Negative

Resistive Plate Chamber

Resistive plate chambers (RPCs) are gaseous parallel plate detectors that combines the spatial resolution of the wire chambers with the good time resolution typical of a scintillation counter. It is therefore well suited for fast space-time particle tracking as required by many trigger circuits in particle and nuclear physics. RPCs do not use wires, are very simple to manufacture and commercially available. RPCs usually operate with voltage differences between 9 and 12 kV, which may also be achieved using both positive and negative high voltage power supplies.



Resistive plate chamber

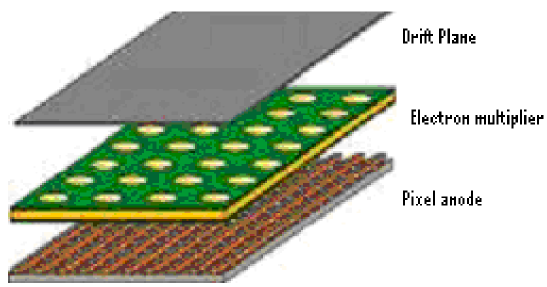
RPC Detectors Power Supply Requirements	
Typical Voltage	9 – 12 kV
Typical Current	1 uA / m^2
Polarity	Positive and Negative

GEMs

The Gas Electron Multiplier (GEM) is a proven gas detector technique that can be used for detecting in position ionizing radiations such as charged particles, photons, X-rays and neutrons, and has therefore a wide range of application, from healthcare to instrumentation for high energy physics.

It uses a thin sheet of plastic coated with metal on both sides and chemically pierced by a regular array of holes a fraction of a millimetre across and apart. Applying a voltage across the GEM (300 – 500 V typically), the resulting high electric field in the holes makes an avalanche of ions and electrons pour through each. The electrons are collected by a suitable device, here a pickup electrode with x- and y-readout.

Multichannel HV/LV power supplies are the best choise for GEMs.



Gas electron multiplier

GEM Detectors Power Supply Requirements	
Typical Voltage	300 – 500 V
Typical Current	1 – 10 mA
Polarity	Positive or Negative

Electrostatic lenses

Electrostatic lenses are often used for beam line steering and diagnostics as well as in a wide variety of applications like time-of-flight and mass spectrometry, ion traps, ionization experiments, … .

Power supply requirements depend on the application and can cover a large voltage range between a few 100V up to hundreds of kilo volts. Typically only low currents are needed. In some case bipolar high voltage may be needed to allow changing polarity of the electrostatic lenses.

Electrostatic Lenses Power Supply Requirements	
Typical Voltage	0 to 100 kV (may vary)
Typical Current	1 uA .. 10 mA
Polarity	Positive and Negative, Bipolar

Low Voltage Power Supplies

Powering Analog and Digital Front End Electronics

In the last decades, thanks to the miniaturization trend in microelectronics, it has been possible to integrate more and more electronic components into particle detectors, in order to achieve significant noise reduction and faster processing. Every detector with built in electronics needs stable low voltages for ananlog and digital circuits. Multichannel silicon strip detectors, PMTs, wire chambers, RPCs may require low voltages, and since each detector type has its own geometry and space constraints, the cable length to the power supply may range from centimeters to several hundreds of meters. Wiener offers approaches to all LV installation challenges: power supplies which are able to maintain a constant voltage over long distances, magnetic and radiation tolerant power supplies which must operate very close to detectors, multichannel HV/LV integrated power supplies, high power devices.

LV Power Supply Requirements	
Typical Voltage	1.5 – 60 V
Typical Current	1 – 200 A
Polarity	Positive or Negative

Power Supplies for Magnets

Power supplies for conventional magnets are usually low or medium voltage, high current units. Depending on the size and coil design of the magnet DC power of a few Watt to hundred of kilo watts can be needed.

Power supplies for quadrupole magnets are typically in the 1 to 6kW class, with maximum currents of 10 to 50A and voltages below 100V. Since most standard magnets have inductances of ten Henries or less, already 10V across the magnet will produce a minimum charge rate of up to 1A/s. Common slew rate requirements are 1A/s up to 50A/s. The resistive load of the magnet coil is often below a few Ohms.

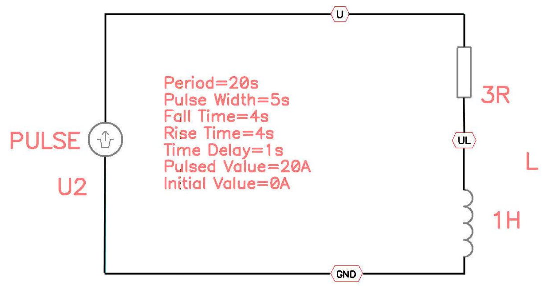
Depending on the application either a true bipolar current output, i.e. a power supply that is able to ramp continuously from full negative current to full positive current, or a polarity switching at zero crossing may be needed.

In order to achieve high precision magnet operation there are extremely high requirements for the resolution of current setting and measurement, in particular the stability and reproducibility. Typically a smooth continuous operation with high setting resolution and low drift over time of 100ppm or less is required. Changing currents has to be possible with adjustable slew rate and should run without overshooting or ringing upon reaching the new operating current. Correction and hysteresis cycles require a defined reproducibility.

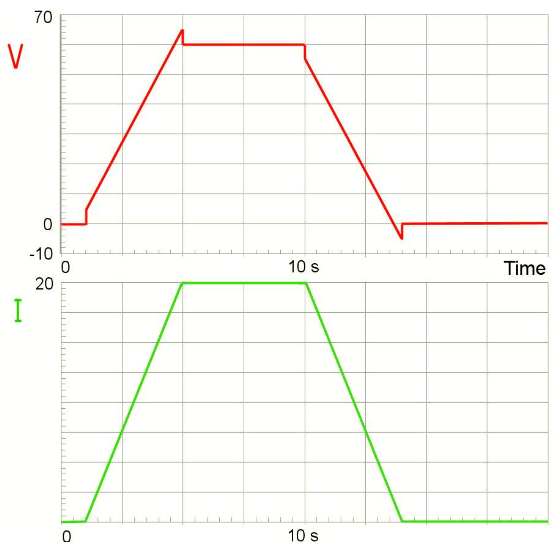
Magnet power supplies should have low noise DC outputs, especially in the low frequency range. Due to the large impedance of the magnet, the high frequency noise of the power supply is often less important than the stability, or long term drift of the current.

For integration in the beam control system remote control and monitoring of the power supply in addition to local operation is often required.

Wiener is developing high precision FET current controlled bipolar power supplies that will be launched in the near future. Primary powered with a high efficient low noise switching power supply the full bridge bipolar FET current regulator is feed only with minimum necessary voltage. That keeps the unit cool and dimensions low.



Simulation of operation of a bipolar power supply (source diagramm)



Simulation of operation of a bipolar current controlled power supply (voltage and current vs time)

Introduction to power supplies and regulation

A voltage regulator is an electrical regulator designed to automatically maintain a constant voltage level.

Most active voltage regulators operate by comparing the actual output voltage to some internal fixed reference voltage. Any difference is amplified and used to control the regulation element. This forms a negative feedback servo control loop. If the output voltage is too low, the regulation element is commanded to produce a higher voltage. For some regulators if the output voltage is too high, the regulation element is commanded to produce a lower voltage; however, many just stop sourcing current and depend on the current draw of whatever it is driving to pull the voltage back down. In this way, the output voltage is held roughly constant. The control loop must be carefully designed to produce the desired tradeoff between stability and speed of response.

Linear Regulated Power Supplies

Linear regulated power supplies consist of a big transformer operating at the mains frequency of 50/60 Hz that produces the low voltage, a rectifier that lets the current flow in one direction only, a regulating device (FET or bipolar transistor operated in its linear region, Zener diode operated in the breakdown region) that keeps the voltage constant and many capacitors.

The regulating device is made to act like a variable resistor, continuously adjusting a voltage divider network to maintain a constant output voltage.

Linear regulated power supplies have the advantage of very "clean" output with little noise introduced into their DC output.

Switching Mode Power Supplies

A switching mode power supply is an electronic power supply unit that incorporates an input rectifier and filter, an electronic switch (chopper) whose AC output at typical frequencies of 50 kHz to 1 MHz is connected to the primary winding of a high frequency transformer, an output rectifier and output filter and a feedback circuit for the regulation that stabilizes the voltage by controlling the timing of the chopper.

Switching regulators are used as replacements for the linear regulators when higher efficiency, smaller size or lighter weight are required. They are, however, more complicated and their switching currents can cause high frequency noise problems if not carefully suppressed.

Comparing linear vs. switching power supplies

In order to determine whether a linear or a switching power supply should be choosen for an application, some facts must be taken into consideration:

- Linear power supplies are best when low output noise is required
- Linear power supplies are best when a fast response to input and output disturbances is required
- Switching power supplies are best when power efficiency is critical
- Switching power supplies are required when only DC is available as input and a higher output voltage is required
- The low frequency transformer of a linear power supply is several times larger and heavier than a corresponding transformer in a switching power supply
- Switching power supplies operating with AC input from the main require a Power Factor Corrector (PFC) in many countries
- Switching power supplies produce radio frequency noise

In many cases either one would work.

Voltage Loss on Cables

Voltage drop is the reduction in voltage in an electrical circuit between the source and load. This voltage reduction may be neglected when the impedance of the interconnecting conductors is small relative to the other components of the circuit. Excessive voltage drop will result in unsatisfactory operation of electrical equipment.

In electronic design, various techniques are used to compensate for the effect of voltage drop on long circuits or where voltage levels must be accurately maintained.

Voltage drop can be reduced with large cable sections, but the drawbacks are higher costs and larger cable capacitance.

The general formula to calculate voltage drop is

$$V \sim \rho\, I\, L / \sigma$$

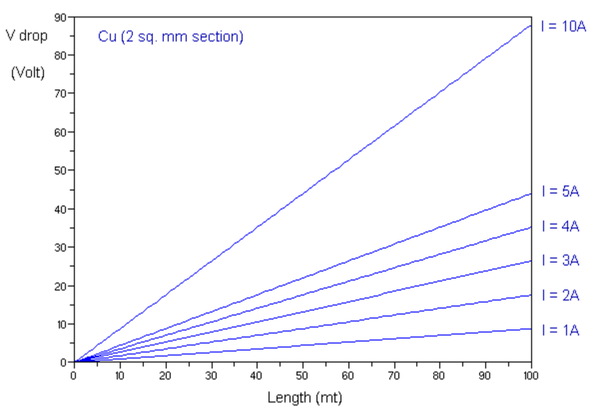
where ρ is the conductor resistivity, I is the current, L is the length of the cables and σ is the cables section. Assuming constant resistivity (although resistivity may depend strongly on temperature and purity), it is possible to draw tables of voltage drop's dependency on the other three variables.

Voltage drop table for 10 A over 100 m of copper wire (in red cells the cable section is not allowed for 10A)

mm	mm²	AWG[1]	Ω/m	Ω	ΔV
0.81	0.52	20	0.352	3.52	35.2
1.04	0.85	18	0.207	2.07	20.7
1.26	1.25	16	0.141	1.41	14.1
1.60	2	14	0.0879	0.879	8.79
1.95	3	12	0.0586	0.586	5.86
2.52	5	10	0.0352	0.352	3.52
3.19	8	8	0.0220	0.22	2.20
5.25	20	4	0.00879	0.0879	0.879

Voltage drop table for 100 A over 100 m of copper wire (in red cells the cable section is not allowed for 100A)

mm	mm²	AWG	Ω/m	Ω	ΔV
5.25	20	4	0.00879	0.0879	8.79
6.68	35	1	0.00502	0.0502	5.02
7.98	50	0	0.00352	0.0352	3.52
9.44	70	000	0.00251	0.0251	2.51
11.0	95	0000	0.00185	0.0185	1.85
12.36	120	250kcmil	0.00147	0.0147	1.47



Above: voltage drop as a function of cable length. Below: some materials resistivities are reported for reference.

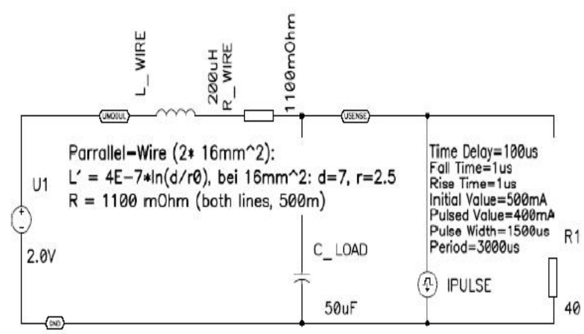
Material	Resistivity (Ωm) at 20°C
Silver	1.47×10^{-8}
Copper	1.72×10^{-8}
Gold	2.44×10^{-8}
Aluminum	2.82×10^{-8}
Tungsten	5.6×10^{-8}
Brass	0.8×10^{-7}
Iron	1.0×10^{-7}
Platinum	1.1×10^{-7}
Lead	2.2×10^{-7}

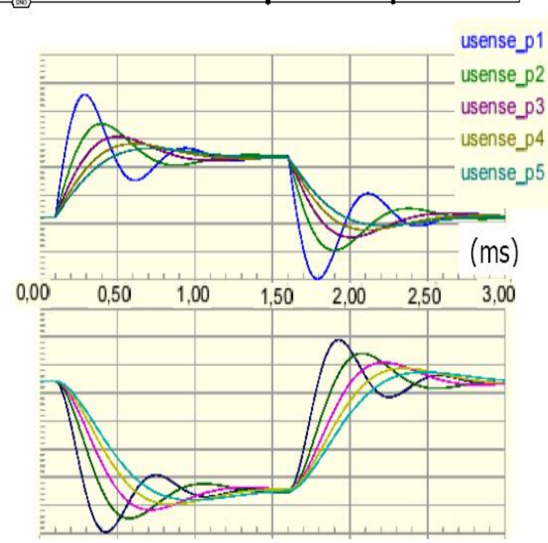
Power Supplies over Long Distances

Long cables are often required to keep power supplies away from hostile environments or to meet particular requirements with space constraints.

Then main challenge that is faced when powering low voltage lines (as low as 1.6 - 2V) over long distances is to get a stable voltage at the load without increaing cable sections too much. The voltage drop along the cables is often considerably higher than the voltage required by the load. In order to determine whether a particular setup will actually provide a stablity that satisfy user requirements, many parameters such as cable capacitance, resistance, voltage regulation time, etc. should be evaluated and optimized within a simulation.

Wiener has a long track record of references in successfully providing long distance power supply and has simulation tools to make sure that user requirements are met. The example below is a preliminary estimation for a 500 meter distant multichannel sink with constraints on cable diameter.





Simulation for a 500m distant sink. Sensed voltage and current versus time for 1,5 ms long current pulses.
p1, p2 - p5 equivalent to C load 50, 100 - 250µF

[1] American Wiring Gauge

Magnetic and Radiation Tolerant Power Supplies

In many cases it may be more convenient to operate the power supplies close to the detector, even in a hostile environment, rather than using long cables. This makes sense whenever the power supply is able to withstand the hostile conditions for a sufficient long time.

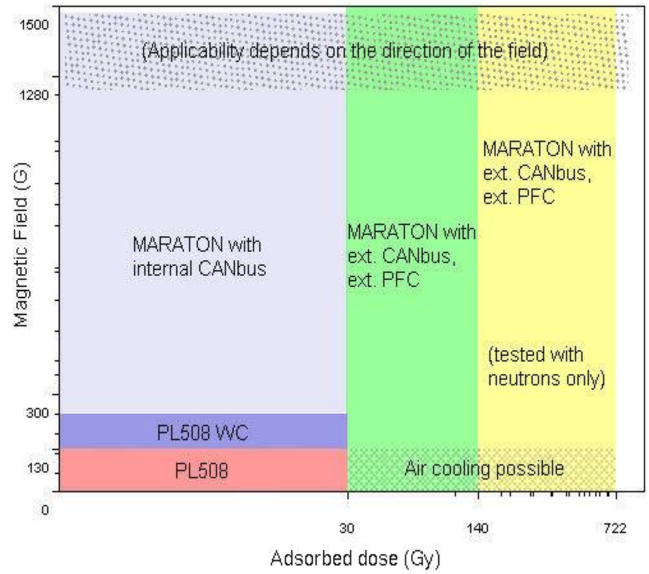
While standard Wiener power supplies can work in lower magnetic fields without further provisions, for higher than 300 G B-fields special screenings for the magnetic sensitive parts inside the power box have to be foreseen.

To provide sufficient cooling, even in higher magnetic fields where motor driven fans are not able to work, a high efficient water cooling system has been developed.

The PL 5-/PL 6- and MARATON series power supplies can be divided into:

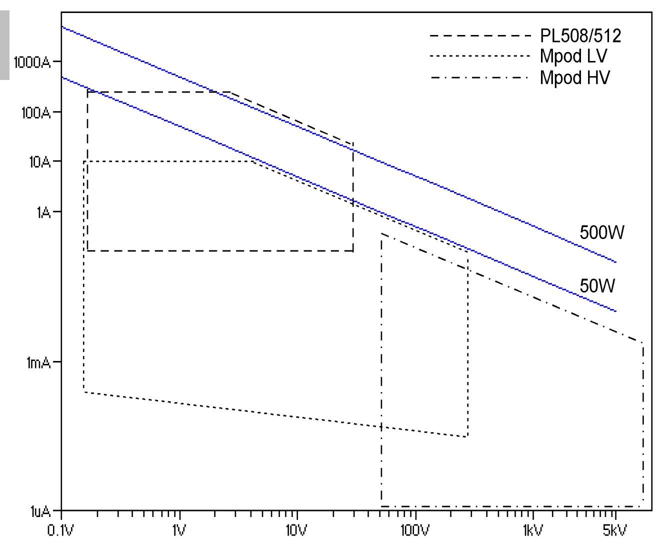
1. suitable for safe environment only (PL 500 /PL 6-)
2. suitable for moderately hazardous environment with low B-field and low radiation (PL 5-WC[2] / PL 6-WC)
3. suitable for hazardous environments with up to 1500G B-field and full CERN LHC radiation spectrum / dose (MARATON, MAgnetism and RAdiation TOlerant New Power Supply System).

WIENER solutions for radiations and magnetic fields:



Summary WIENER Low and High Voltage Power Supplies

Device	Voltage Range	Wiener Solution
PMTs	1 – 3 kV	*Mpod* HV
Si PMTs	25 – 70 V	*Mpod* LV
APDs	50 – 2 kV +/- 5V	*Mpod* HV-LV
Si detectors	50 – 500 V +/- 2 to 5V	*Mpod* HV-LV
Ge detectors	4,5 kV +/- 2 to 5V	*Mpod* HV-LV
Wire chambers	0,5 – 10 kV	*Mpod* HV, special HV
RPCs	9 – 12 kV	*Mpod* HV
GEMs	300 – 500V	*Mpod* HV
Special LVs for A/D	1,5 – 60 V	PL508, PL512: I > 10A/ch
Special LVs for A/D	1,5 – 60 V	*Mpod* LV, I < 10A/ch.
Electrostatic Lenses	0 – 100kV	*Mpod* for up to 10kV, *Mpod* for 0.5 / 3kV bipolar, ISEG stand alone <100kV



Voltage and current requirements and Wiener solutions (per channel).

[2] WC: Water Cooled