

Basics of High Voltage Probe Design

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Samuel M. Goldwasser
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Preface

Author and Copyright

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DISCLAIMER

The devices, equipment, circuits, and other gadgets described in this document may be dangerous. Much of it deals with potentially lethal voltages. Getting electrocuted could ruin your whole day. Using an inadequate or improperly designed or fabricated high voltage probe to measure high voltage can be equally dangerous.

We will not be responsible for damage to equipment, your ego, blown parts, county wide power outages, spontaneously generated mini (or larger) black holes, planetary disruptions, or personal injury that may result from the use of this material.

For really high voltage equipment, also see: [Tesla Coils Safety Information](#).

WARNING: The microwave oven is perhaps the most dangerous equipment you are likely to encounter around the house. The high voltage (up to 5,000 V) along with the high current (1 A or more) availability make this an instantly lethal combination. It is highly recommended that NO measurements be made on a powered microwave oven. Only after the plug has been pulled and its high voltage capacitor has been safely discharged should you even think about touching or probing anything. Most troubleshooting can be done with at most an ohmmeter. See the document: [Notes on the Troubleshooting and Repair of Microwave Ovens](#) for more information. By comparison, TVs, monitors, and even large helium-neon lasers, are tame. While still very dangerous, they don't have quite the deadly quality of the microwave oven!

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Introduction

Scope and Purpose of This Document

There are all sorts of times when being able to determine the value of a high voltage DC source is desirable. Most multimeters have a maximum range of 750 or 1,000 V. (One exception is the workhorse Simpson 260 which has a 5,000 V range). Whether testing a TV with a dim picture, a helium-neon laser power supply that does work quite right, or troubleshooting some home-built high voltage project, the ability to measure 10, 20, 30, or more kV can come in handy.

This document provides information on constructing very basic high voltage probes suitable for measuring the high voltages found in consumer electronic equipment like TVs, monitors, and microwave ovens (though the latter is not recommended for safety reasons).

These simple approaches will work for DC and low frequency AC voltages but no effort is made to compensate for stray capacitance - which will seriously limit high frequency response. However, some of the issues are discussed.

If you will be making HV measurements regularly, by all means invest in a real HV probe for your multimeter. A commercial HV probe will still be a far better long term investment than some cobbled-together unit. However, for occasional HV testing, what is described below can be built and used safely but probably won't have the accuracy, consistency, or frequency response of a good commercial probe. Aside from purchasing a HV probe new, these do show up surplus as well as on eBay, possibly at greatly reduced prices. Even if a model isn't available for your particular multimeter (which is likely), it should be possible to adapt almost any commercial probe to work with it, requiring at most a scaling factor when taking a reading.

SAFETY

Read the associated document: [Safety Guidelines for High Voltage and/or Line Powered Equipment](#) before attempting to work with high voltage systems. High voltage can jump amazing distances when you least expect it. The direct or indirect consequences of this can ruin your entire day or a whole lot more.

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High Voltage Probe Design

Basic Considerations

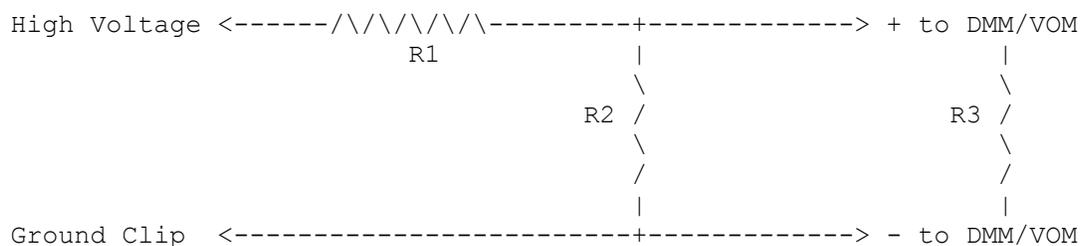
CAUTION: DMMs may not be particularly forgiving of voltages on their inputs exceeding their specifications. Autoranging DMMs may be even more likely to blowout as they are selecting the correct range - if there even is one. Depending on your electrical and mechanical components, the chance of excess voltage due to arc-over, leakage, or component breakdown may be a major consideration. My analog VOM has survived many close encounters with HV. You should not assume the same for the typical low cost or even expensive DMM. There is a reason for the high cost of commercial HV probes - these kinds of factors are incorporated (hopefully) in their design.

A simple high voltage probe for a DMM or VOM may be constructed from a pair of resistors. This is suitable for DC measurements but without compensation, will have a unknown AC response due to the very high impedance and stray capacitance forming a filter - low pass or high pass depending on the amount of stray capacitance and input capacitance of your meter or scope. However, this simple design is sufficient for the majority of consumer electronics work which are mostly DC measurements. I have not characterized the AC response of this probe design. However, if there is AC riding on your high voltage, it may mess up your readings if there is no compensation provided as it may act as a high pass filter.

To design the voltage divider, the input impedance of the meter must be taken into account. There is a minor but significant difference between DMMs and VOMs.

- DMM: Z-in is usually constant, often 10M ohms.
- VOM: Z-in is the voltage range (full scale) times the ohms/volt rating of the meter.

Here is the basic circuit:



R1 together with R2||R3 form a voltage divider where R3 is the internal resistance of the DMM or VOM on the scale for which the probe is designed.

While R2 is not strictly needed, it is recommended that it be included and approximately equal to the Z-in of the meter on the scale you will be using. The reason to include R2 is to insure that high voltage never can reach the meter. The ground clip should be securely connected to the metal chassis of the device being tested - the frame of a microwave oven or CRT grounding/mounting strap of a TV or monitor - before it is powered up. Both R1 and R2 should be located in the probe head.

The only difficult part is locating a suitable resistor for R1 that has high enough resistance and physically is long enough such that arc-over is avoided. The only difficult part is locating a suitable resistor for R1 that has high enough resistance and physically is long enough such that arc-over is avoided. [Caddock](#), [OhmCraft](#), [Victoreen](#), and [Vishay](#) are among the major companies that manufacture suitable resistors. But don't expect them to pay much attention to you for an order of 5 resistors! However, it may be possible obtain free samples if you explain what you're doing - and their lawyers don't get involved! If this doesn't work out, electronics surplus outfits occasionally come up with odd lots of strange components such as these and they even show up on eBay from time-to-time.

The high value high voltage resistor can also be constructed from several equal lower value resistors in series if they are all approximately the same size. Another possibility is salvaging the focus divider networks from dead flybacks or TV/monitor voltage multiplier assemblies. Even if the unit was discarded as being faulty, where there are no internal shorts in the HV rectifier or resistive network itself, the entire unit can be used intact.

In addition to basic safety precautions when working around high voltages, some form of equipment protection should be considered in provide an arc-over path to ground should there be arcing over the surface of the resistor as well as if the resistor should somehow decrease in value. There is no telling what can happen under less than ideal damp or dirty conditions.

A 'corona', 'arc', or 'discharge' ring could be placed around the resistor near the low voltage end securely connected to the ground cable. The idea is that any arcing over the surface should find this as its destination before obliterating your meter.

A variety of devices could be placed across R2 to limit the maximum voltage present in the event of a breakdown. Suitable devices include neon light bulbs (NE2s without resistors); zener, avalanche, or ordinary diodes; or other semiconductor junction devices. Traditional surge suppressors like MOVs and Tranzorbs may work but their off-state impedance may be too low compared to R2). The neon bulb is good since its impedance is essentially infinite until its breakdown of 90 volts or so is reached. In some cases, these devices will be destroyed (semiconductors may short) but they will have served their protective function and are a small price to pay to prevent you and your meter from being blown.

Frequency Response

Probe compensation similar to that used on oscilloscope probes can be implemented. However, the determination of the capacitor values is beyond the scope of this note. To put it simply, the ratio of the capacitance C1:C2 (where C1 is across R1 and C2 is across R2||R3) needs to be equal to the ratio of R2||R3 to R1 (or equivalently, to the inverse of the voltage divider ratio). C2 includes the stray capacitance and input capacitance of the meter or scope probe. The capacitor across R1 would need to sustain the HV so that is another complication. Since a 10x scope probe usually has an input impedance of 10M, the same design as used for the DMM would work with a scope. Although I have not pursued this issue, it sounds like based on the ratio (1000:1 would mean that C1 would need to be extremely small, probably smaller than the stray capacitance of the R1 and the associated wire) you would need to add a capacitance for C2 and that there will be enough stray capacitance such that no physical C1 will be needed.

If you are only interested in DC measurements, putting a .1 uF capacitor across R2 should smooth out any 50/60 Hz or higher frequency ripple.

The implementation of full probe compensation is left as an exercise for the motivated student.

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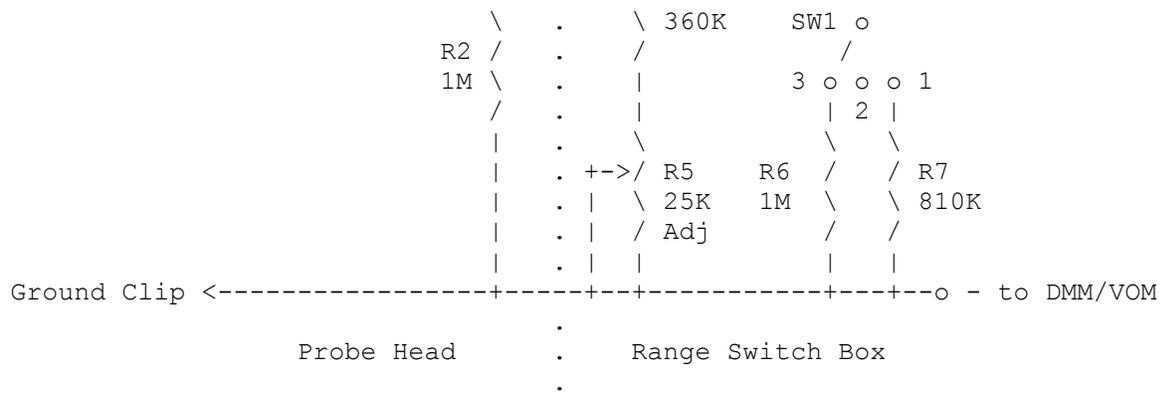
Simple High Voltage Probe Design Examples

50,000 V Maximum Using a 10Mohm Z-in DMM

By my rule above, I will select R2 to be 10M ohms. Fine adjustment of calibration could be made by making R2 out of a combination of a fixed resistor and a multiturn pot.

To minimally load the circuit under test, R1 should be as high as practical. Practical here means (1) low enough so that leakage over its surface is not a problem, (2) low enough that a reasonable voltage can be developed across R2||R3, and high enough so that loading of equipment being tested will not change the readings by more than a few percent.

R2||R3 is 5M ohm. Selecting R1 to be 4,995M ohm will give a 1000:1 ratio so that 50,000 volts will read out as 50 V on the DMM. 4,995M ohm is high enough that loading of a 250M ohm focus network should not be an issue (5%). 1000:1 is a nice easy to remember ratio. You could go to something higher if loading is still a concern but then leakage current over the surface of R1 becomes an even greater



- SW1 - SPDT Center Off Toggle Switch.
- All resistors except R1 are 1/4 watt 2%.
- 50,000 V maximum based on the particular R1 I had laying around. 1000:1 voltage division.
- SW1-1 = Radio Shack DMM on 3, 30, or 300 V scale (10M Zin).
- SW1-2 = VOM, 25 V scale (30K ohms/V, 750K Zin).
- SW1-3 = VOM, 100 V scale (30K ohms/V, 3M Zin).

Modifications to use a higher value R1 are straightforward.

Calibration

Unless you have a calibrated HV supply, a working TV for which you have the service manual makes a good starting point. The proper high voltage is usually specified to within 5-10%. If you have a line-transformer based HV supply (e.g., neon sign transformer, rectifier, capacitor), then this would be pretty accurate based on your power line voltage. For a DMM with a constant input resistance, you can use a low voltage (like a few hundred V) on a lower range and extrapolate for the HV range. However, for a VOM, you cannot use this technique since changing ranges also changes the parallel resistance of R2||R3. You are already using nearly the full sensitivity of the meter.

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More Information on High Voltage Probes

Construction of High Voltage Probes

(From: Duane C. Johnson (redrok@pclink.com).)

1. When you make the resistor strings make sure that the maximum voltage rating of the resistors is not exceeded. Most resistors have a maximum rating of 200 volts. In this case I would not exceed 100 volts per resistor.
2. Don't place the scope directly in series with the higher resistors. The first resistor should be in parallel with the scope and ground or the scope chassis.

This detail is important for safety reasons. If the connection to the scope becomes disconnected

then their will not be a dangerous shock hazard as would be the case if the scope was in series.

(From: Larry G. Nelson Sr. (nr@ma.ultranet.com).)

You can do this with a high voltage resistor divider network. That is what is in a high voltage probe you would buy. This can be very dangerous to you and your equipment in the event of a failure. Please be very careful. I suggest a fuse at the probe input and an MOV across the resistor to ground that will connect to the scope and use a plexiglass tube to put it all in to contain the bits if anything blows up.

(From: Kevin Astir (kferguson@aquilagroup.com).)

With respect to preventing high voltage arcing and corona, **do not** use RTV.

Places that carry the GC line will have some 'anti corona discharge dope' often called 'Q-dope'. This is **the** stuff to use at HV. You can clean it off with acetone when you discover that you didn't clean flux off good enough and have an arc underneath. Epoxy and RTV have no such advantage, and RTV releases corrosive acid while curing to boot.

Heed the warnings of other respondents WRT resistor voltage. As they said 100 V per for garden variety resistors will yield a safe margin. 200V is typical max rating.

There are special HV resistors (up to 10 kV or so) made, available into the G Ohm range. I don't know of a hobbyist source however. If you know anyone who works in nuclear instrumentation field they may be able to snag one for you. (HV used as detector and PMT bias in radiation detectors). This is what will be inside "real" HV probe from Fluke, or Tektronix.

Finally, I have a lot of experience, and am fairly blase' around HV, but in addition to "normal" 115V AC rules, (no rings, one hand in pocket, etc.) I **never** work on HV stuff (not even a TV or hi-pot test) alone. And, I make sure the 'observer' knows CPR, even if I have to wait 2 days to fix TV, so girl friend can 'help'.

High Voltage Probe Frequency Response

(From: Winfield Hill (hill@rowland.org).)

You can calculate this for yourself. The parasitic lead-to-lead capacitance of a typical small resistor is 0.05 to 0.2pF. The capacitance from the **middle** of the resistor and from any connection node between series resistors, to ground, may range from 1pF to 5pF or more depending upon your choice of a shielding scheme. Longer glass resistors intended for high voltages have lower lead-to-lead capacitance, but higher distributed parallel capacitance.

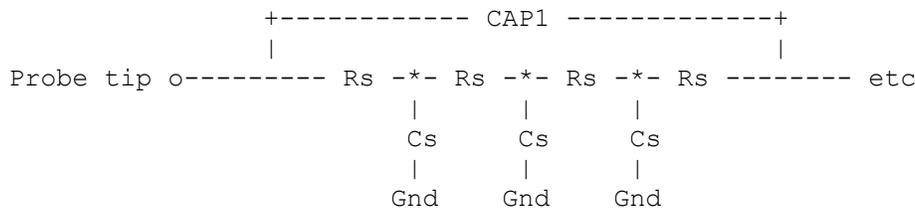
As a worst case, imagine a 1000M ohm probe made with a 2-inch long resistor. To start, place the capacitance to ground from the midpoint. If you assume 5pF of parallel capacitance, you'll see you're in trouble even at 60Hz!

- HV probes with usable high frequency response may have cleverly arranged shields which can be connected to ground, the attenuated signal output, and the input. Some shields may overlap and may be adjustable, to provide an adjustable capacitive divider that can swamp the remaining effects of the resistor's capacitance.
- These probes can be very accurate at DC and high frequencies, but the skill of the designer is tested in the transition between resistive and capacitive divider action. They can be very badly behaved in this transition region. Basically the "center" of the resistor experiences a bypass to ground (a severe dip in gain) or due to other HF components, a severe peak in gain. This can easily be 50% and cover a decade. Typically it'll happen at 20 to 100 kHz.

One solution invokes the capacitance from a few carefully-placed concentric sleeves connected to the input and the signal output, plus an overall shield or guard connected to ground.

- Poorly designed probes can suffer from mid- or high-frequency errors and from severe pickup sensitivity to nearby rapidly-changing voltages. For example, I've seen probes that provide an output even when the measuring tip is grounded!

The classic low-voltage probe architecture of a pair pf RCs doesn't work for HV scope probes, unless (1) you're willing to have an overly high capacitive loading, or (2) you don't care about mid-frequency or pulse-shape response accuracy. This is because the RES1 value will be very high, 100M or more likely 1000M ohms, and physically long and large. So the real circuit is like:



Because the Rs are so high, the probe becomes a good antenna, and a shield is mandatory. Therefore the Cs "stray" capacitance is higher than you might think. I think you see the problem.

One solution is to make C1 very large, but it's just a matter of specs - if you want 1% performance over the whole range, C1 is a severe load. There is a good overall solution, which I think is fairly clever (after thinking of it, I discovered the experts had beat me to it!).

High Voltage Probes for AC Measurements

(From Winfield Hill (hill@rowland.org).)

The usual method is simply to use a capacitive divider, a small 1 kV capacitor, etc., or make the HV capacitor yourself for really high voltages, like 5 to 20 kV, use an air neutralizing capacitor, etc.

Say for example, its a 3pF capacitor. With shields. With another more conventional capacitor, say 3000pF for the bottom of the attenuator, followed with a voltage buffer if desired, and you've got a nice wide-band 1000:1 HV probe installed in the system, good for mucho kV.

More on Measuring High Frequency High Voltage

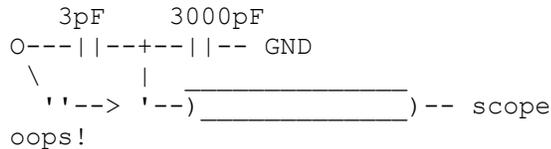
(The following was prompted by a request to measure the pulses in a capacitive discharge ignition system.) (From: Winfield Hill (hill@rowland.org).) You want to measure the voltage pulse or spike, so you'll need a high voltage high-frequency probe. Many popular HV DC probes are not suitable, such as the Fluke 80K-40 probe. Fluke does have a high-frequency HV probe, the PM9100, which is a 200 MHz, 4 kV probe. For voltages higher than 4 kV, use a Tektronix P6015A probe (buy one on eBay), or you can make a probe yourself.

First let me strongly say that designing HV AC probes which include a resistor for DC measurements is not trivial. Read the rest of this document including my other comments on this subject in the previous sections.

You can see details of an impressive 500 kV five-foot probe design, [Rob's High Voltage Probe Page](#). Lacking a shield, this probe is suitable only for DC or low-frequency AC use.

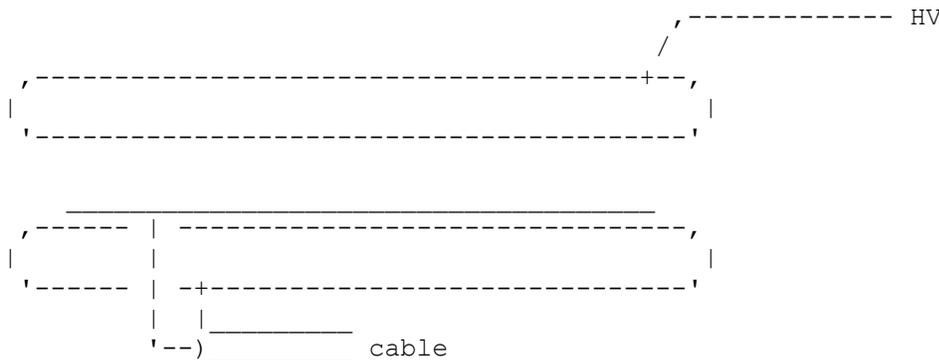
For your purposes a simple ac-only probe should suffice. Happily they are relatively easy to make. The basic principle is to make a capacitive divider. For example, a 3pF HV input capacitor with a 3000 pF load capacitor will make a 1000:1 divider with perfect high- frequency response. You can use a home-made 3 pF, 30 kV air capacitor.

Used with a standard 1M scope input the probe will have a 3 ms droop time constant and low-frequency roll-off of 53 Hz. This is suitable for measuring all kinds of fast HV signals like auto ignition pulses, camera-flash triggers and discharges, TV flyback transformer outputs (before the HV diodes), Tesla-coil primary voltages, atomic-trap ring voltages, etc. A 30 kV input will present a safe 30 V to the scope.



Sounds simple, but there are a few problems. A big one is labeled oops! on the drawing above, namely unplanned capacitive paths from your HV signal to the divider junction. To prevent this you'll need some cleverly designed shields.

Because your 3 pF capacitor must be able to withstand 30 kV, it'll be much larger than you would at first imagine. For example, I have used two 1/4-inch thick 4-inch diameter discs placed 1/2-inch apart, IIRC, held in place by metal bars to a long ceramic rod located off to one side. Both discs had 1/4" rounded sides to prevent corona discharge. The "lower" disc was grounded to act as a shield. The low-voltage sense electrode was a thin copper shim-stock disc with a slightly smaller diameter, stuck to the ground disc with double- sided mylar tape. A hole in the ground disc allowed a coax cable connection to the copper sensing disc.



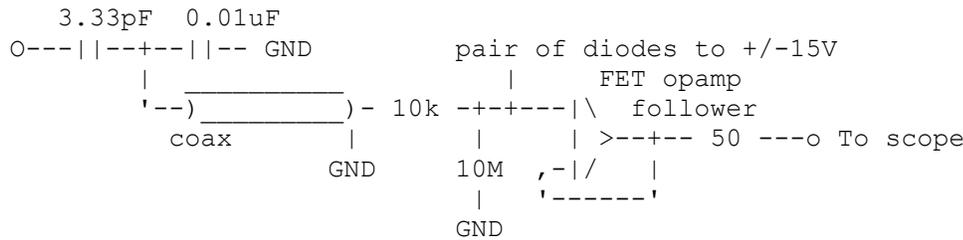
Keep in mind that you should get zero output with the HV probe tip grounded - with the wrong shield layout this is a tough requirement.

A smaller design might use two concentric metal tubes, with an outer shield and an inner low-voltage electrode. The HV would be presented on a wire held in place in the center, making only 3pF of capacitance to the inner tube. Holding the wire in place with a sturdy tip mount without unduly increasing the capacitance would be a design issue.

Calibrate the probes with low voltage AC signals and an AC RMS DVM.

A second issue is protecting the scope. You have to absolutely sure your homemade 30 kV capacitor will not have a small breakdown event and destroy your scope! One solution is to make a 1:3000

divider so the output is limited to 10 V and use a diode-protected opamp follower. Also, with the 10M resistor the droop time constant is better, 100 ms and the low-frequency -3dB point is lower, 1.6 Hz.



Commercial High Voltage Probes

(From: Frank Miles (fpm@u.washington.edu).)

Both Tektronix and Hewlett Packard sell HV probes rated at 5kV and up. Bandwidths are (at least) into the 100kHz area, probably more. I imagine there are others.

The older Tek probes even had ports to refill with now-banned chemicals. The newer ones don't, but are more expensive.

Frequency response is a significant concern. Designing and manufacturing a decent HV probe is definitely non-trivial if you need flat frequency response. Many parts have significant voltage coefficients, too, as well as breakdown voltages.

(From Winfield Hill (hill@rowland.org).)

A significant part of the design effort (and cost) deals with, the problem of how to go smoothly from a resistive divider at low frequencies, to a capacitive divider at high frequencies, while keeping a constant attenuation value at mid-frequencies. This isn't easy. Consider for example, that an overall shield is clearly needed and must properly prevent the high-Z end of the probe from simply acting as an antenna (as some HV probes do! i.e. ground the tip of the probe and *still* see large signals at the output). This shield acts as a capacitance to ground for the HV resistor, routing some of the high-frequency current which is supposed to go to the output, to ground. Hence at some middle frequency there's a dip! This is solved in various ways - with shields connected to the probe tip (but inside the ground), capacitors bypassing the resistor, special resistor construction, etc. Most solutions can just as easily cause a region with a response hump, as well as a dip, or even both. BTW, these problems are much harder if one seeks to make a probe with very low capacitive loading and high frequency response. The Tek P6015A probe is 3pF, and you'll also note it has a veritable raft of response adjustments on the scope-input end.

Much of the cost of the probe is knowing how to do all this!

Incidentally, a low-cost intermediate-range HV probe is the Fluke PM9100, which is a 4kV 100:1 probe with a 200MHz bandwidth. Also the Tek P5100 is rated to 2.5kV. Most of these probes also have a derating above some frequency.

Most of this mess you can avoid entirely by not attempting to make the probe measure DC (or at least not the whole frequency range).

(From: Sam.)

The person who contributed the following comments may not be totally unbiased but the information is

still valid.

(From: Cichel Clenci (cichel@cic-research.com).)

I used many different probes on high voltage measurements and found out that their performance is terrible when exposed to even relatively low common mode voltage transients (100 V or more). Even when using differential probes like Tektronix's P5200 or P5205 measurements can be influenced by common mode voltage transients. You will get glitches on the output that are not there, these will confuse the engineers. One big problem is the high input capacitance of the probe. In order to get the best common mode rejection of the various transients and an accurate representation of the input waveform, you must reduce the input capacitance. 4 pF or 3 pF input capacitance is too high, when dealing with high voltage fast transients, and the compensation is not as easy as it might seem. Look for 0.5 pF or lower input capacitance. There are many issues that need to be addressed when designing high voltage (differential probes). Just take a look at [CIC Research HV Probes Page](#) for probes that outperform Tektronix's or LeCroy's probes.

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