EAGLE HARBOR TECHNOLOGIES

EHT Technical Note #1
High Voltage Nanosecond Pulse Measurement Techniques

Ilia Slobodov

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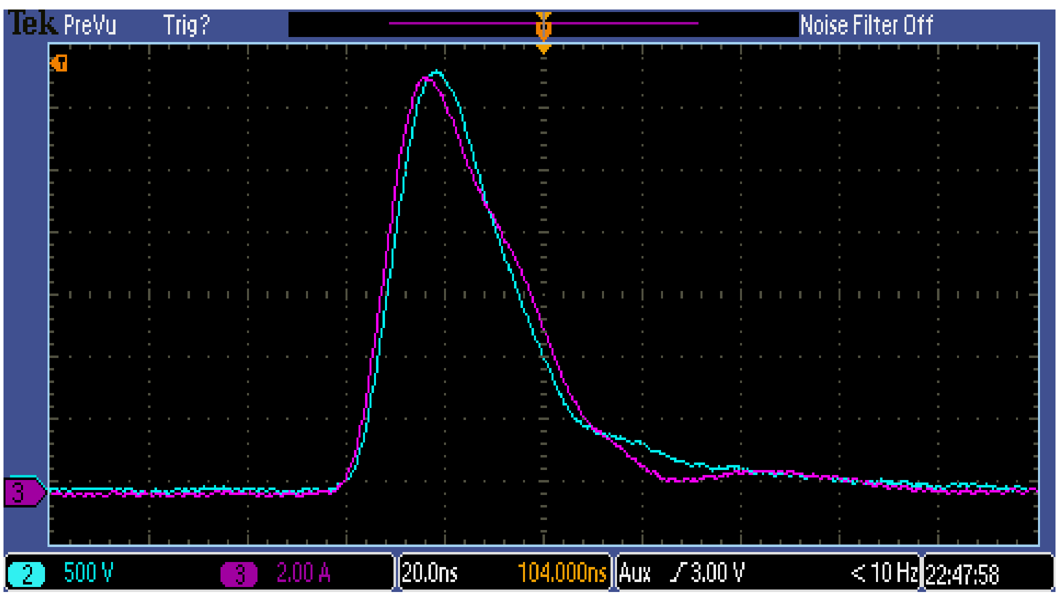


PRELIMINARY

!!! Extreme Danger !!!

This document describes measurements of the high voltage outputs of EHT Nanosecond Pulsers. The energy levels, voltages, and/or currents used and generated by these units can be lethal. The pulser should only be operated by qualified personnel. Do not attempt to operate the power pulser unless the user has sufficient knowledge of the dangers and hazards of working with high voltage. Do not attempt to approach or touch any internal or external circuits or components that are connected or have been connected to the power supply and pulser. Be certain to discharge any stored energy that may be present before and/or after the power supply and pulser is used.

Table of Contents

Introduction

The EHT nanosecond pulser series of power supplies generate pulses that are both high in voltage, up to 40 kV, and have fast rise times, as short as 10 ns. The measurement of these kinds of waveforms represents unique challenges and requires specific techniques to be able to achieve believable results. This document will discuss methods for measuring both the voltage and current of these waveforms reliably and will explain the common problems experienced when making such measurements. It will also describe equipment that is known to EHT to produce accurate results.

Measurement Equipment

EHT standardly uses the following set of equipment that has been found to produce adequate results when making high voltage nanosecond pulse measurements.

1. Tektronix DPO-2024 Oscilloscope

   These oscilloscopes from Tektronix allow interfacing to their high voltage differential probes.

2. Tektronix THDP0100 High Voltage Differential Probe

   This is a 6 kV probe with 1 pF of input capacitance and a 100 MHz bandwidth. It is important to always use a differential probe for performing these high voltage measurements, because single sided (grounded) probes introduce an extra ground point into the system, shifting the output potential and introducing the possibility of additional noise.

3. Stangenes Industries SIT 30-250 Isolation Transformer

   EHT formerly used these transformers to float the oscilloscope during measurement, however it has been found that this is not necessary. Nonetheless, if it is necessary to float some components of the experimental system, this is a reasonable transformer to use.

4. HVR Advanced Power Components RT/RL series resistors

   These 2W 7kV resistors which come in values from 10 Ω to 47 kΩ have been found to perform well under pulsed high voltage conditions. They have minimal stray inductance and stray capacitance compared to other resistors EHT has tried.

5. Pearson Electronics 6585 Current Transformer

   This current transformer has a fast useable rise time of 1.5 ns which is necessary for measuring the fast outputs of EHT nanosecond pulsers.

Other equipment with similar characteristics may also be suitable.

Measurement Setup

In order to get a reliable measurement of the output waveform, there are several important considerations. The ideal measurement would be done with a probe that had no stray capacitance and no stray inductance and infinitely high input impedance. Furthermore, the system under measurement would be far away from all other objects and therefore have no stray capacitive coupling to anything else. In practice, none of this can be achieved and the experimenter must take care to minimize the error that arises from all of these factors.

Stray Capacitance

The stray capacitance between the system and its surroundings can have a significant impact on the measurement. For example, if a pulser has output leads several meters long going to the load, and these leads are allowed to lie on or near a metal table, this can contribute tens or hundreds of picofarads (pF) of stray capacitance. In many cases, the user's load may be a dielectric barrier discharge with a capacitance of just several pF, and in such cases the stray capacitance may not only throw off the measurement but dominate the behavior of the system overall. Therefore, it is important to keep any output leads away from metal surfaces or any other objects to which there can be any significant amount of capacitive coupling. This also applies to the load itself, ideally, it should be kept physically far away from everything that is not part of the system.

Resistive Dividers

Because EHT nanosecond pulsers can generate high voltage pulses up to 20 kV (or even higher in some cases), and high voltage differential probes typically have a maximum voltage rating no greater than 6 kV, it is usually necessary to measure the output through a voltage divider.

All real resistors have some associated parasitic capacitance and inductance. Depending on how a resistor is built, these components can be very large and may impact its response to an input signal. Furthermore, the impedance of resistors may be voltage dependent under pulsed power conditions. EHT has empirically demonstrated that the resistance of a resistor subject to a high voltage nanosecond pulse may be up to 30% lower than its rated DC value. This phenomenon depends on the size and type of resistor, with higher value resistors typically losing a higher % of their DC resistance than lower value resistors. In EHT's experience, the RT series of resistors from HVR Advanced Power Components have minimal stray inductance and stray capacitance in comparison to other HV resistors and also behave well under pulsed power conditions.

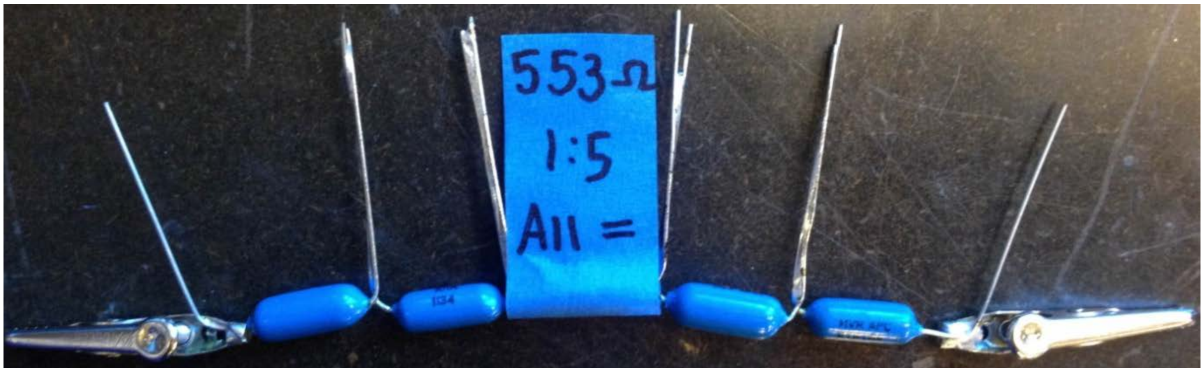
The total resistance of the voltage divider may be application-specific, and the impact of having the voltage divider impedance in parallel with the load should be considered. The current drawn by the resistive voltage divider is easily calculated (I = V/R) and if it is not much smaller than the current drawn by the actual load, than it is too disruptive to the system and will throw off the measurement. However, the resistance of the voltage divider cannot be too high, since high voltage differential probes typically have capacitance of 1-2 pF, and a proper measurement needs to resolve features with 10 ns timescales. This usually places an upper bound on the resistor value of 5-10 kΩ.

The user must also ensure that if the resistive divider is too be used during continuous operation rather than just individual pulses, that the resistors are sized adequately to handle the power that will go into them ($P = V^2/R * T * f$).

Additional guidelines:

- Construct voltage dividers with resistors of all equal values. Equal valued resistors will all change their resistance by the same amount when exposed to fast high voltage pulses, maintaining the same overall division ratio.
- Always use an odd number of resistors, so that the probe can be clipped across the central resistor.
- Do not use too many resistors in a voltage divider chain, as longer chains become more inductive, which introduces its own distortion into the waveform.

An example voltage divider can be seen in the picture below.



This voltage divider has been constructed with 5 x 110 Ω resistors in series for a total resistance of ~550 Ω. Therefore, clipping across a single resistor gives a voltage division ratio of 1:5. The total resistance and voltage division ratio have been labeled, as well as “All =” which indicates that the resistors are all of equal value. The resistors were soldered as close together as possible to minimize the stray inductance of the entire chain, and alligator clips were soldered on either side of the voltage divider to facilitate attaching it across any arbitrary output. The leads of the resistors were not twisted together before soldering to make de-soldering as easy as possible if necessary. This voltage divider is composed of all HVR RT series resistors.

Capacitive Voltage Dividers

In some cases, it may not be possible to select a resistive voltage divider that both allows for a short enough RC time to resolve the signal features of interest while pulling a low enough current to avoid affecting the system. In these cases, it may still be possible to make the voltage measurement, using a capacitive voltage divider instead. It is important to select capacitors that perform adequately under pulsed high voltage conditions (typically, high voltage polypropylene film capacitors work well). It should still be kept in mind that the capacitance of this capacitive divider will have to be charged in parallel with the user’s load, and can introduce its own distortion.

Additional guidelines to keep in mind with capacitive voltage dividers:

- Keep the capacitance of the divider low compared to the load being measured
- Keep the capacitance of the each capacitor in the divider high compared to the stray capacitance of the probe (typically 1 pF) clipped across the central capacitor
- Ensure that the RC time of the capacitor being clipped across with the probe input impedance (typically 1 MΩ) is much longer than the features of the waveform being measured (since the capacitor will discharge through the probe on this RC time)

Grounding

Any grounds in the system should be explicitly defined and understood by the user. Typically, an EHT nanosecond pulser has a floating output stage, such that both outputs (positive and negative) are galvanically isolated from ground. Typically, the load is also kept floating. In this standard case, grounds come into the system at two locations: the AC cord providing power to the EHT pulser, and the AC cord providing power to the oscilloscope used to measure the waveform.

Standard grounding practice calls for a single star point ground, and therefore it may be tempting to float the oscilloscope using an isolation transformer or battery power supply. However, in order for this to be effective on the relevant timescales, the stray capacitance of the isolation transformer from the primary to the secondary, or the stray capacitance of the battery power supply to its surroundings, must be small compared to the stray capacitance of the EHT pulser's output stage (typically ~30 pF). In practice, commercially available isolation transformers have too high of stray capacitance, and battery power supplies are physically large enough that their stray capacitance to their surroundings is too high.

Therefore, it is best to explicitly ground the oscilloscope. This creates a ground loop in the system, and so the system must be used in such a way as to minimize the effects of this ground loop. The majority of applications of EHT nanosecond pulsers do not involve inductive loads that generate magnetic fields, and so the potential for picking up flux with the ground loop to produce noise is limited.

However, when a probe is connected to the system, even a differential probe, it is still "aware" of the oscilliscope's connection to ground. Therefore, if the probe is connected to the system in some location, it introduces a "knowledge" of ground to that location. If no probe is present and the output is floating, the potentials on the output will want to arrange themselves such that the system is in the lowest possible energy state. What this means is that if ground is at 0V and we have a unit with a 20 kV floating output, the negative output lead will come to –10 kV and the positive output lead will come to +10 kV. Now, if the user connects a probe lead directly to, for example, the negative output, then the system will instead come to a potential closer to 0V on the negative output lead and +20 kV on the positive output lead. This costs additional energy relative to the lowest energy state, and the current needed to come to this arrangement of potentials will couple through the probe and oscilloscope, causing significant distortion to the measured signal. Not only does this cause the probe to measure the waveform incorrectly, but it actually changes the underlying waveform as well, and may cause safety issues with some EHT pulsers that are not designed to handle this configuration.

This is why it is important to always clip across the center resistor of a voltage divider as described in the previous section.

These considerations are slightly different if measuring the output of an EHT pulser which is specifically designed with a grounded output. For positive polarity grounded output units, the negative probe lead should be attached directly to the negative (ground) high voltage output.

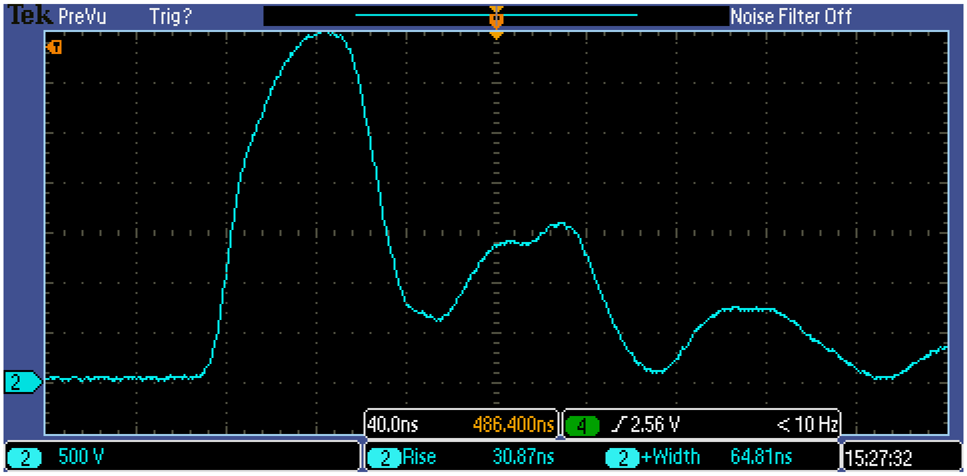
Reflections and Load Matching

If long output leads are used, reflections of the signal may travel back through the cables and introduce additional complexity to the measured waveform. An ideal measurement would have the effects of reflections minimized. There are two approaches to limiting the effects of reflections.

The first is to limit the length of the output cables going from the EHT pulser to the load. In general, a "short" output cable means that the propagation time of the signal through the cable is short compared to the signal's fastest characteristic timescale (usually the rise time). The propagation speed of a signal through a cable is given by $v = c/\varepsilon^{1/2}$. Typical dielectric constants are on order of 3-4 so it is reasonable to approximate that signals propagate through cables at about half of light speed (c, in convenient units, is 1 ft/ns). Therefore, if a signal has a rise time of about 10 ns, then the cable must be kept shorter than 5 ft to be effectively "short" for the purpose of reflections. If a long cable must be used but the user is willing to sacrifice rise time, then a series output resistor can be used to slow the rise time (due to the RC with the cable's and the load's capacitance), allowing for a longer output cable before reflections become a problem.

If it is not possible to keep the cable sufficiently short, then the other approach is to match the cable impedance to the load impedance. The characteristic impedance of a cable is given by $Z = (L/C)^{1/2}$. The characteristic impedance of easily manageable coaxial or twin lead cables usually ranges from about 25 Ω to 400 Ω. Producing reasonable cables that are easy to work with outside this range of impedances can be difficult, but specialized custom cables may be possible to create. If the load is primarily resistive in this range, then it is easy to match the load impedance to the cable. However, often the load of interest is dominated by a capacitive rather than a resistive component. In this case, the user can consider placing a resistor in parallel with their load in order to match the cable impedance and eliminate reflections.

If neither of the above options is practical, then the user may be stuck with a waveform that includes reflections and is therefore not as ideal in appearance. However, depending on the physics of the application, a waveform with reflections may still be acceptable. Below is an example of a waveform with a set of reflections due to being at the end of a 20 ft cable.



General Cleanliness of the Experimental Setup

Usually, an experimental setup with high voltage measurement will include several individual pieces of equipment and their associated cabling. These typically include the EHT nanosecond pulser, the load being driven, the output cables, the oscilloscope and probe(s), a high voltage DC charging supply, and possibly a signal generator to drive the EHT nanosecond pulser. All of these pieces of equipment will also have power cords. With this large number of individual pieces of equipment, it is easy for an experimental setup to quickly become a "mess" with cables going everywhere.

In the experience of EHT, it is very valuable to layout the experimental system in a clean manner, with no cables crossing each other. The goal is to maintain the experiment in a state where it is visually easy to confirm that everything is connected correctly. This has the important added benefit of minimizing stray capacitance between different pieces of equipment. Fiber-optically coupling the signal generator to the oscilloscope and EHT pulser is also key to prevent current being able to flow between these pieces of equipment.

Always inspect an experimental setup for general neatness of layout and do not allow it to devolve throughout the course of work. This is also of key importance to maintain high voltage safety.

Summary of Measurement Setup

Here is a brief summary of the things to ensure in order to have the best chance of getting believable high voltage measurements:

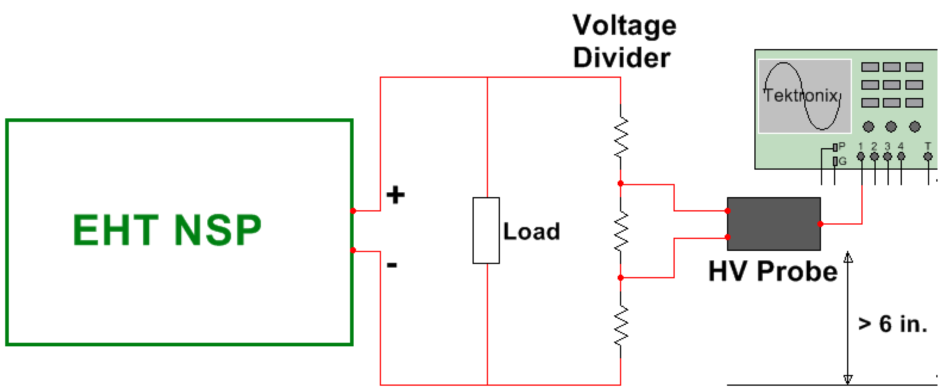
- Minimize stray capacitve coupling from the outside world to the output leads, probe leads, oscilloscope, load, and any other system components
- Measure the voltage with a high voltage differential probe across the central resistor of a voltage divider composed of identical value resistors, of a series known to perform well for fast high voltage pulses
- Either use short output cables or match the cable impedance with the load impedance
- Maintain a clean, neat setup which is visually easy to inspect and avoid crossing cables

Measuring the Output Waveform

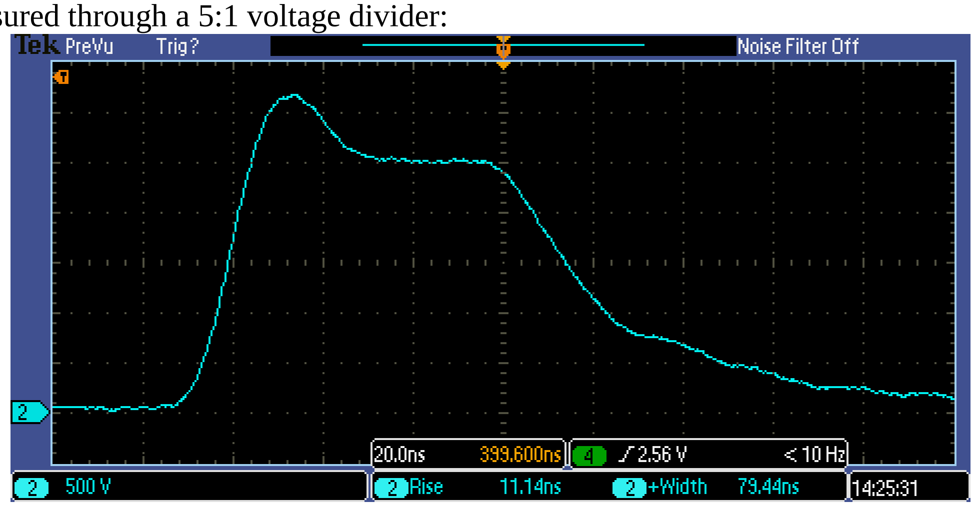
With the hard work of preparing to measure high voltage nanosecond pulses accurately as described in the section above completed, here are the measurements that are typically made and how to make them. The motivation for making these measurements can be to determine exactly how much energy or power is being delivered to the load, to tune in the pulse width precisely, or to verify that the system and load are working as expected. The measurements of interest may include voltage or current or both.

Voltage Measurement with a High Voltage Differential Probe

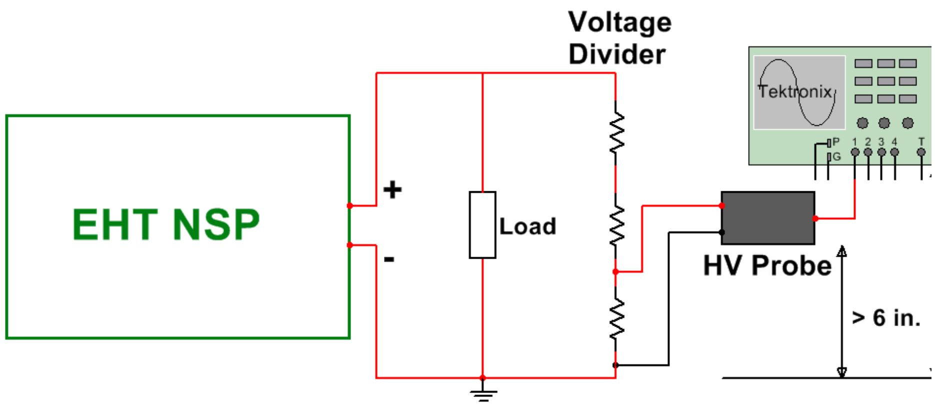
For floating output units, clip the high voltage differential probe across the center resistor of a voltage divider as shown in the diagram below.



First, try to take a measurement with the resistive voltage divider as the only load, as this is the simplest case and allows the user to verify that the measurement system is working properly. The measured waveform should closely match the waveforms should in the manual for the product in question, such as for example the waveform below which is from an NSP-5000 driving a 517 Ω load, measured through a 5:1 voltage divider:



In the case of a grounded unit, clip the probe across the first resistor on the grounded side, as shown:



Remember that the stray inductance and capacitance of the probe leads matters and can affect the signal. It is usually desirable to reduce the stray inductance of the probe by making sure that the two probe leads run close together and parallel to each other, rather than forming a large loop. Stray capacitive coupling to other objects must be minimized. Stray capacitance can be an especially significant problem if working on a metal (or other conductive) surface. If the work table being used is a metal table, the entire experiment and all of its components and diagnostics should be lifted off the table by at least six inches to reduce stray capacitive coupling.

Once signal fidelity has been verified by measuring across a simple purely resistive load, attach the experimental load of interest and repeat. If noise is introduced into the system when connecting the real load, this may be due to EMI, see the section below regarding additional noise reduction measures.

If the voltage must be measured at multiple locations, there are some additional considerations. Each probe has a maximum voltage rating, and since they are all connected to the same oscilloscope (or even different oscilloscopes which are each grounded), then the maximum potential difference between any two probe leads on any probe in the system must be kept within the maximum voltage rating (6 kV for the recommended probe).

Current Measurement with a Current Transformer

Measuring the output waveform with a current transformer is one of the most non-invasive methods of making a measurement. Other non-invasive methods including using D-Dot or B-Dot probes, but these are not routinely used as diagnostic equipment for making high-voltage pulsed power measurements in the nanosecond regime, and may require challenging calibration. In contrast to an HV probe, which adds a high impedance load in parallel with the voltage divider as well as some parallel input capacitance, current probes offer a way of making a measurement without adding a significant stray element to the output circuit. While current monitors will technically produce a "back EMF" in response to the magnetic field established around the current-carrying wire that is being measured, the effect of this back EMF on the circuit is usually insignificant.

To set up for the current measurement, feed one of the output cables through the current transformer. Center the output cable inside the current transformer so that the cable is not touching the walls of the current transformer. Again, this is to reduce the stray capacitive coupling between the cable and the current transformer. It is essential to use a current transformer that has a response time significantly faster than the fastest signal that will occur, otherwise, ringing/oscillations may appear on the output signal.

When using a current transformer, its output is typically connected with a 50 Ω BNC cable to the input of an oscilloscope. This BNC cable must be terminated with a 50 Ω termination at the oscilloscope; otherwise the current signal will exhibit reflections. When the 50 Ω terminator is used, the output signal of a Pearson current transformer is reduced by a factor of 2, since they effectively have a 50 Ω output resistance. This must be taken into account when calibrating the current measurement.

Use RG-223 (not RG-58) BNC cables, which are double shielded for optimal performance.

Measuring the Voltage and the Current Simultaneously

It is possible to make simultaneous measurements of voltage and current. In general, the same rules and safety considerations apply when using current and voltage probes simultaneously as do when using them individually. Try to maintain a clean setup, avoid stray capacitive coupling to either type of probe, and avoid large inductive loops between any two of them.

It is important to note that most current and voltage probes will have a different propagation time for a given signal. Therefore, there can be a delay between when a waveform is measured by the voltage and the current probe. To perform a power measurement, it is desireable to have the current and voltage waveforms displayed at the right timing relative to each other. This can usually be achieved by adjusting an oscilliscope's deskew setting for the relevant channel. To set this up, initially measure the voltage and current going into a simple resistive load (using resistors appropriate for pulsed high voltage applications as described above). Voltage and current should have the same phase in a resistor, so adjust the deskew until the two waveforms overlap exactly in time.

Additional Noise Reduction Measures

In some cases, even following all of the guidelines above, noise may still be present on the measurements. This can be due to EMI production from the load or the EHT pulser, which can be picked up by a probe and produce erroneous signals. This EMI is often worse in dielectric discharge loads (arcs, dielectric barrier discharge, etc), but may be generated solely by the fast rise times into resistive loads. EMI may generate common mode or differential mode noise through either inductive pickup in the leads, or direct interference with the control electronics.

Shielding an HV Probe

If the user suspects that the probe is picking up external noise, it may be beneficial to shield the probe body. This can be achieved by enclosing the entire probe body within metal, such as wrapping it in aluminum foil. The metal enclosure then needs to be grounded to the scope with a low inductance path to ensure a solid ground reference. Keep in mind that the probe may begin to heat up when enclosed in metal since there is no direct or indirect airflow over the body. The user should take precautions to ensure that the probe does not heat up too much. As a general rule of thumb, only use metal shielding when dictated by the testing setup; at all other times it should be removed from the metal enclosure and given adequate airflow. Also, ensure that any foil/shielding used on the probe is kept sufficiently distant from any high voltage points on the input side of the probe.

Using Ferrites to Reduce Noise

Ferrite cores can be utilized to filter out common-mode noise propagating down coax cables and high-frequency voltage fluctuations propagating down other types of cables, such as power cables. Adding ferrites to a cable effectively adds an RL filter that filters out unwanted high-frequency noise. This type of noise is a common source of poor measurements on nanosecond timescales. To properly utilize the ferrite cores, the user should independently wrap the high-voltage probe cable and the current probe cable several times around two ferrite cores. If the HV probe cable cannot fit through the ferrite cores, the user should use 2 – 3 ferrite clamps along the length of the cable (see the image below).

Ferrites can be safely added to most cables in a high-voltage setup. For example, they should be added to the power cord of the isolation transformer (if used), as well as the power cords to any DC supply and/or NSP that are being used. Sometimes noise propagating through a system may find an easier path through ground, thus producing ground currents that can affect systems that appear to be isolated from one another. Adding ferrites to these cords increases their inductive impedance, thus adding an additional layer of isolation between different parts of a system. However, they should not be added to any wires in the output circuit. This would be equivalent to adding an inductor on the output and will change the output waveform.

(Left) Cable wrapped loosely around two ferrites. (Right) Cable passed through a ferrite clamp.

Because ferrites are made of conductive material, the winding of the ferrites must be considered carefully. The stray capacitance of the wire wrapped around the ferrite forms a stray capacitance that is in parallel with the added inductance. If this stray C is too large, it effectively shorts out the ferrite. As a result, it is generally preferable to wrap the wires loosely around the cores as shown in the left image above, to reduce capacitance. In addition, rather than a number of cores with several windings in one spot, it is generally better to use several sets of cores with one or two windings each to reduce the total stray capacitance.

Shielding a Current Transformer

Current transformers are also susceptible to picking up EMI noise. In some cases, shielding the current probe by wrapping it in tin foil can be helpful to reduce this noise. If the shielding is continuous, it will also screen out the magnetic field of interest that allows the current to be measured. Therefore, it is best to leave a thin azimuthal slit along the inner diameter of the current transformer. This will allow azimuthal fields to enter the transformer and be measured, while screening out axial and radial fields.