Pulsed Power Engineering Diagnostics

June 13-17, 2011

Craig Burkhart & Mark Kemp
Power Conversion Department
SLAC National Accelerator Laboratory

- Grounding
  - Proper grounding
  - Ground loops
- Voltage measurement
  - Voltage divider
    - Resistive
    - Capacitive
    - Balanced
  - Commercial voltage probes
- Current measurements
  - CVR
  - Rogowski
  - Self-integrating Rogowski

Grounding References

•M. Thuot, “Resolving EMI Issues to Optimize Accelerator Beam Diagnostic Performance” Beam Instrumentation Workshop 2004

• Ott, Henry W., Noise Reduction Techniques in Electronic systems, Wiley 1988

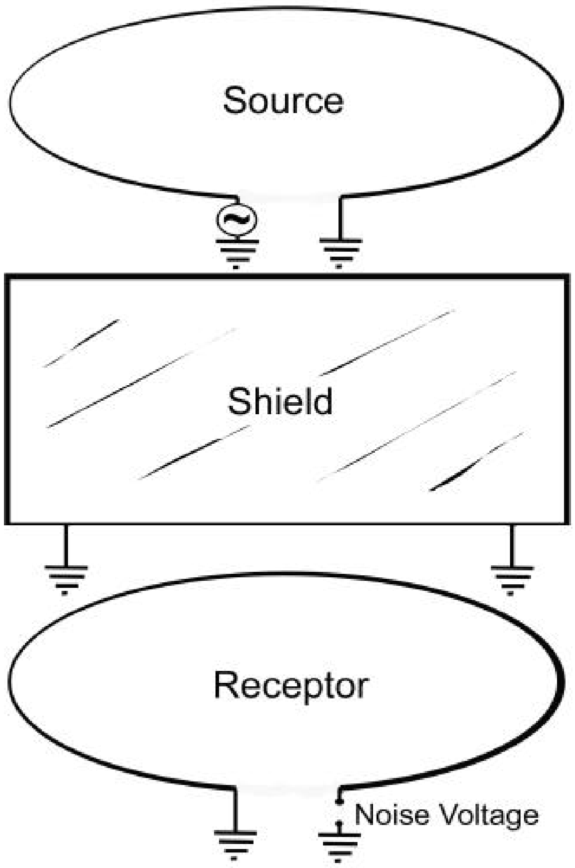
• Paul, Clayton R., Introduction to Electromagnetic Compatibility, Wiley 1992

Grounding

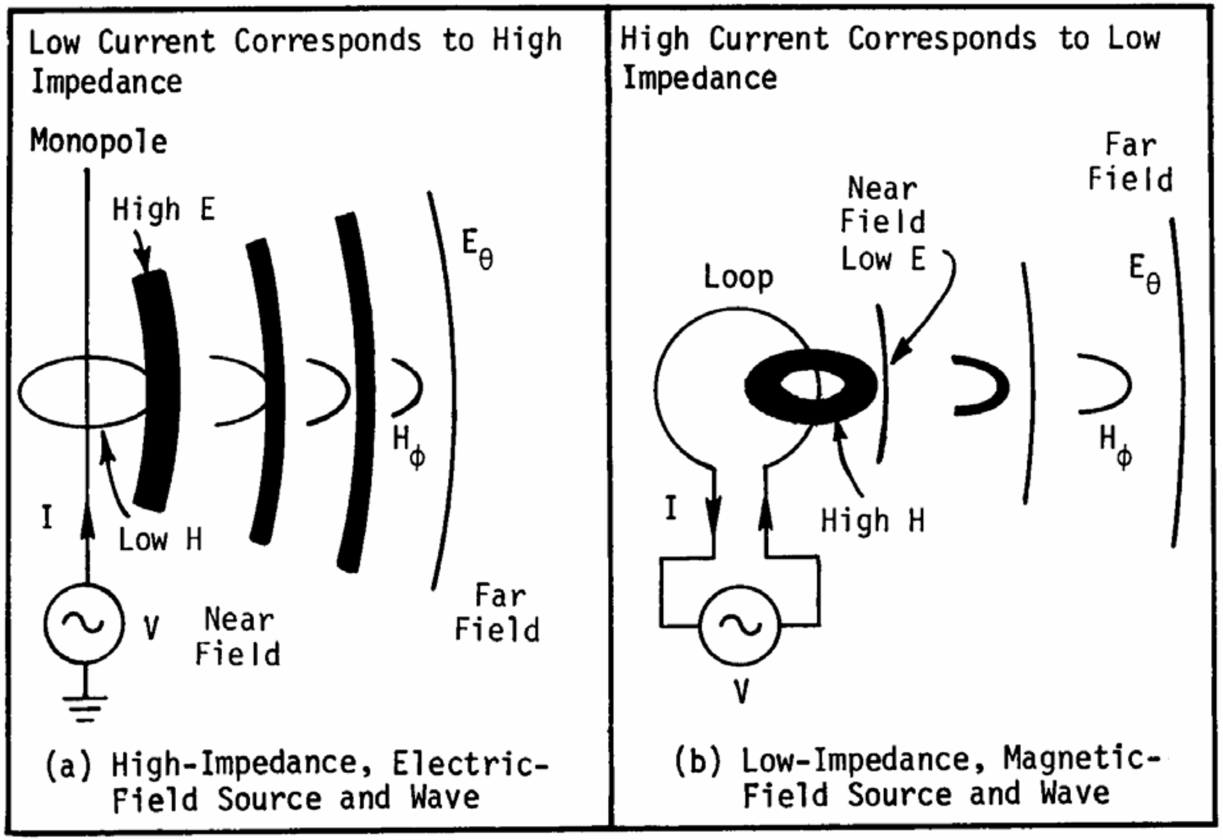
- Proper grounding is the single most important factor in making accurate experimental measurements in pulsed power systems: design it in
- kA/μs X nH = V, no two points in a high dI/dt system ever have the same potential which will induce “ground loop” currents
- Solid “earth” ground when possible
- “Single point” ground systems when possible
  - Almost anything with an AC plug has a ground lead
  - Safety requirements often result in additional grounds
- Use tri-axial cables instead of co-ax, outer shield can be non-current carrying connection required for grounding/bonding

Grounding

- Steps in reducing EMI
  - Mitigate EMI sources
  - Reduce coupling
    - Shield to decrease coupling from radiation
    - Ground properly to reduce conductive coupling
  - Minimize receptor susceptibility to EMI

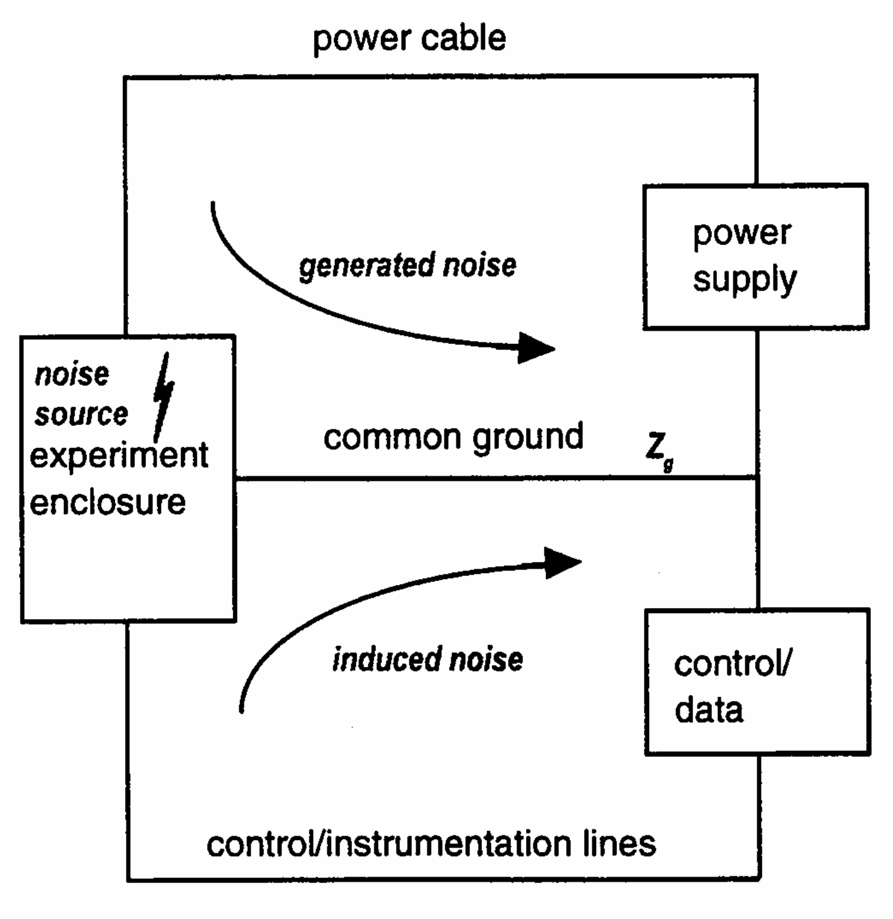


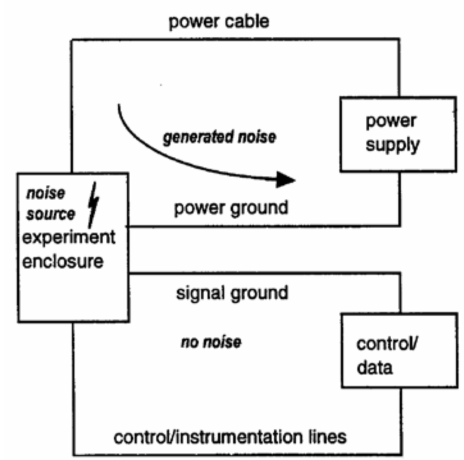
Grounding

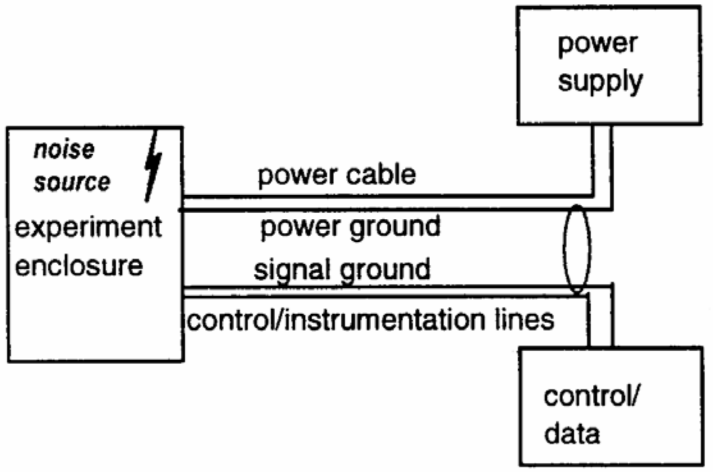


Low Current Corresponds to High Impedance
Monopole
High E
Low H
I
V
Near Field
Far Field
E_θ
H_ϕ
(a) High-Impedance, Electric-Field Source and Wave
High Current Corresponds to Low Impedance
Loop
Near Field
Low E
Far Field
High H
I
V
E_θ
H_ϕ
(b) Low-Impedance, Magnetic-Field Source and Wave

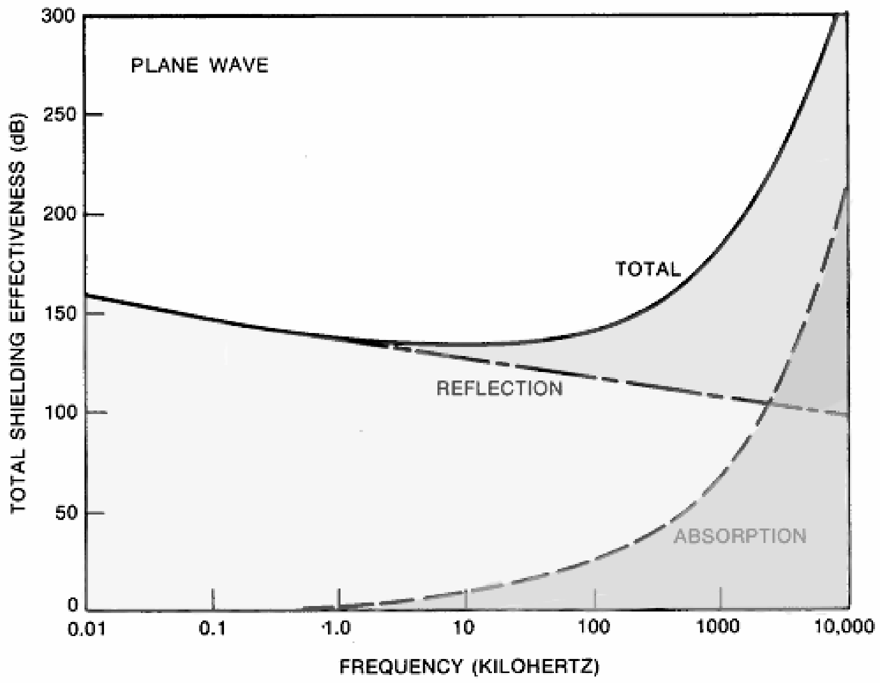
Grounding


power cable
generated noise
power supply
noise source
experiment enclosure
common ground
Z_g
induced noise
control/ data
control/instrumentation lines


power cable
generated noise
power supply
noise source
experiment enclosure
power ground
signal ground
no noise
control/ data
control/instrumentation lines


power supply
noise source
experiment enclosure
power cable
power ground
signal ground
control/instrumentation lines
control/ data

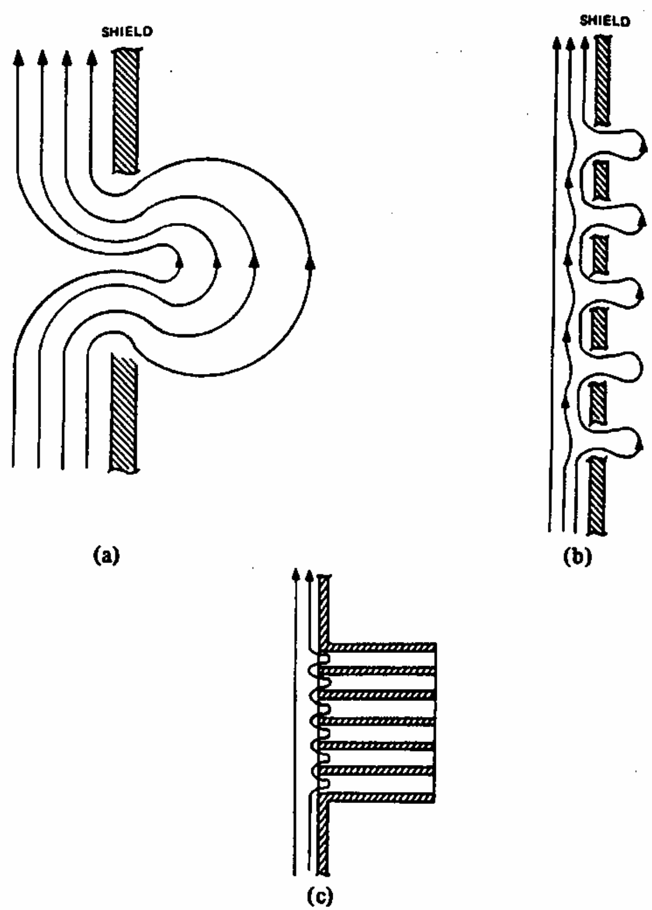
Grounding



Method of shield effectiveness depends on frequency range

- -At low frequency, most incoming radiating is reflected
- -At higher frequency, absorption becomes more dominant

Grounding



Magnetic field penetration of apertures. (a) Single aperture. (b) Many small apertures. (c) Array of waveguides beyond cutoff.

•Screen boxes can be used to reduce coupling to diagnostics and equipment

- •If holes have a linear dimension larger than ~1/20th of the incoming radiation wavelength, it will penetrate into the box

- •Many smaller holes are preferable to a single, larger hole of the same dimensions

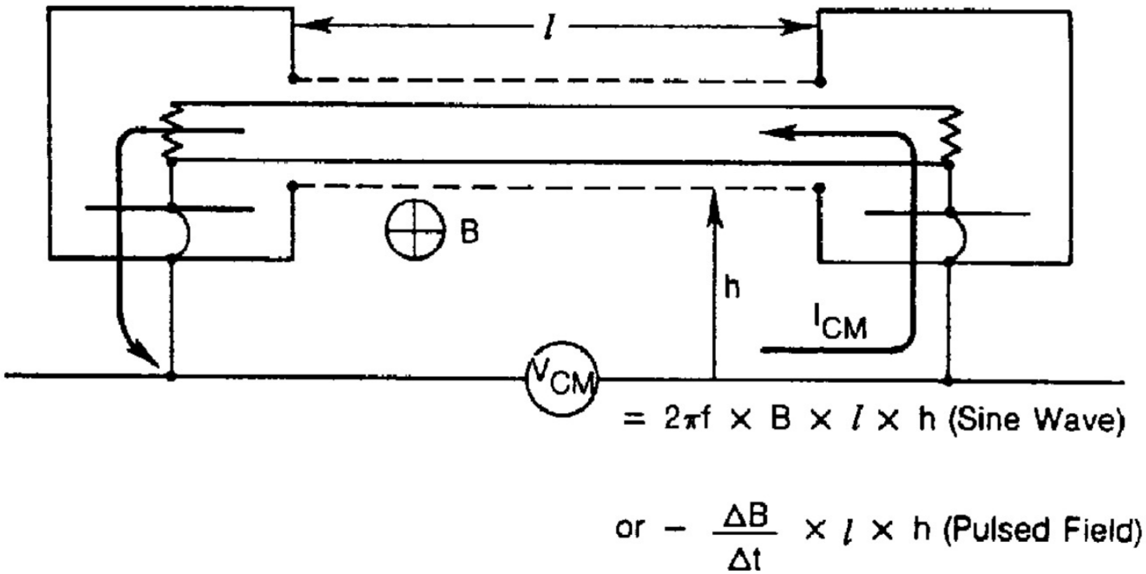
Grounding

1. Mutually ground all operator-accessible equipment to the designated local ground point.
2. Keep currents through shields and ground connections to a minimum. Provide current return paths in the same cable or tray for every source or supply. Do not use thin shields for current return; use balanced sources and cable if possible. Signal cable shields from ungrounded signal sources should be grounded only on one end.
3. Eliminate or minimize conductive cables entering shielded enclosures**.** Position cable entrances near the ground point/power entrance. Use fiber optics or isolators where possible.
4. Power entrances to subsystems often define the ground point. Respect them; group all required ground connections together to minimize currents in shields.
5. Use shielded transformers, properly connected, for power supplies.
6. Completely shield all high di/dt power sources. Noise radiating cables should be shielded and grounded at both ends, run high power cables in metal conduit. Avoid openings or discontinuities in shields whose maximum dimension exceeds ~l/50. Include trigger sources and rf amplifiers inside the shield if possible.

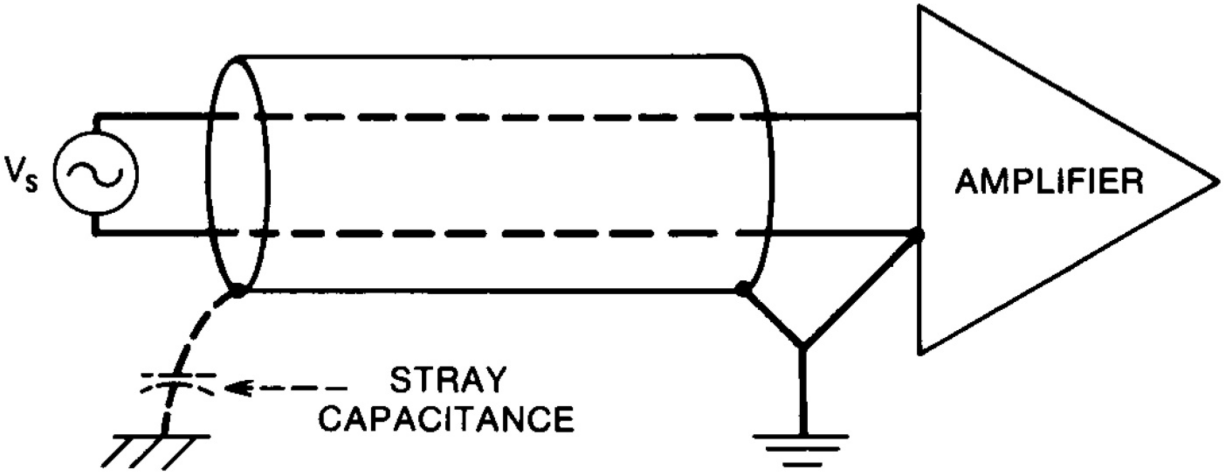
Adapted from Thuot

Ground Loop

DC coupled

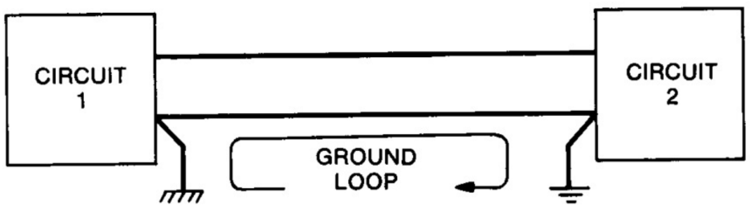


Capacitively coupled

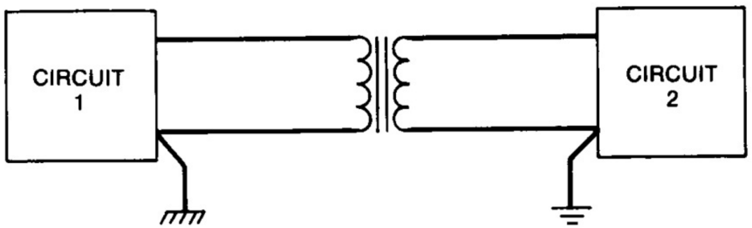


Isolation Techniques for Ground Loops

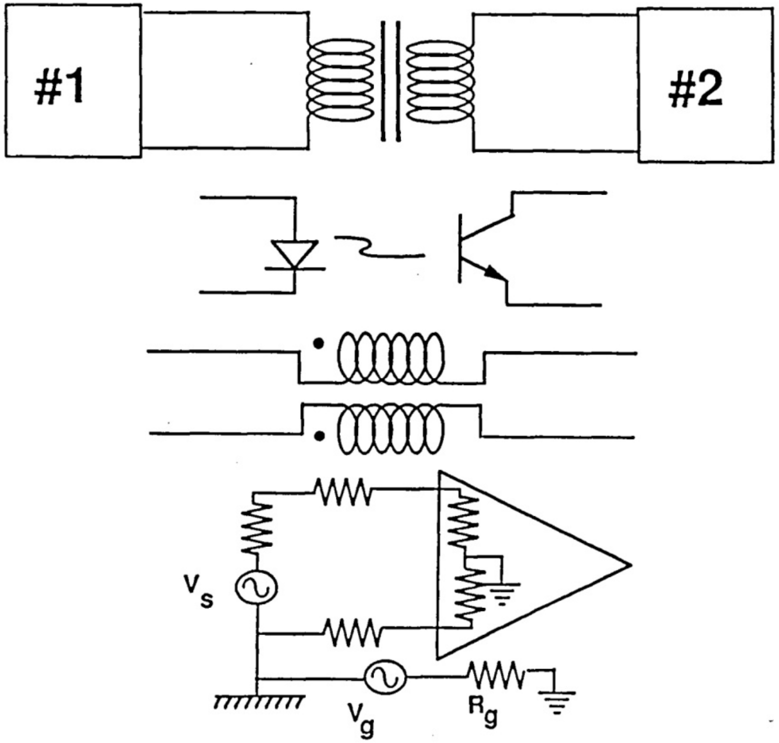
Ground loop from multiple-point grounding



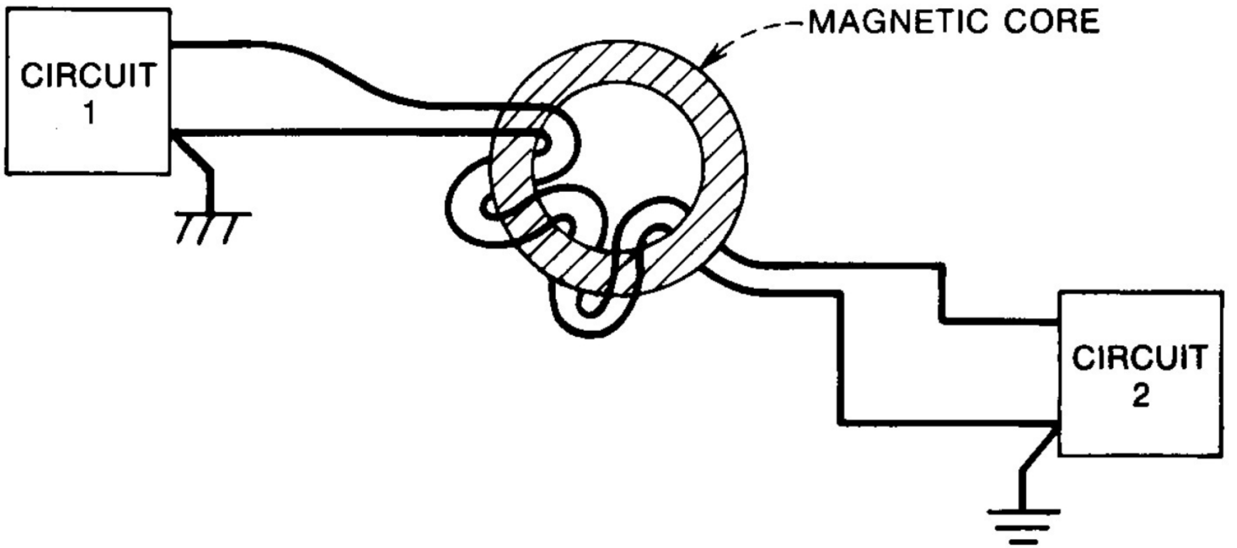
Interrupting ground loop current flow using transformer isolation



Additional isolation techniques



Common Mode Choke for Signal Cables



Safety

- Safety issues in pulsed power is a very important and involved topic
- What is the easiest way to stay safe?
  - Know your system and its associated hazards
  - Properly plan work before starting
- Integration of safety into machines
  - Machine protection
  - Personal protection
  - Engineering controls
  - Administrative controls

Measuring High Voltage

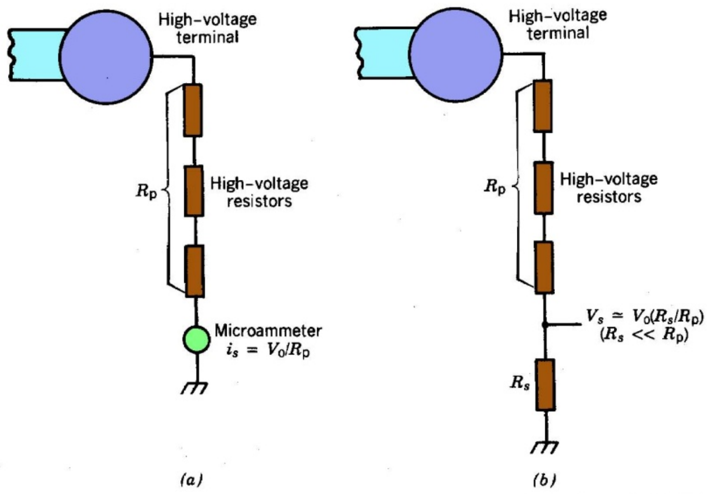


Figure 9.49 High-voltage measurements with resistor strings. (*a*) Resistive shunt. (*b*) Resistive divider.

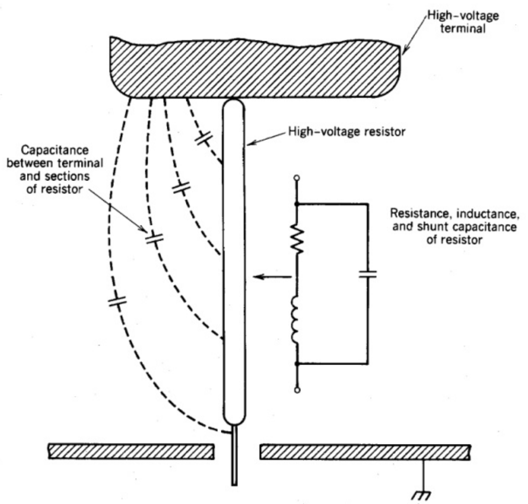


Figure 9.51 Effect of stray capacitance, shunt capacitance, and series inductance on resistive voltage divider.

- High voltage resistor strings are used to make HV measurements
  - Resistive shunts
  - Resistive dividers
- Parasitic effects (illustrated in Fig 9.51) can introduce waveform distortion at higher frequencies as illustrated in Fig 9.52
- Impact of parasitic elements is reduced as resistance of string is reduced, but dissipation and loss increases

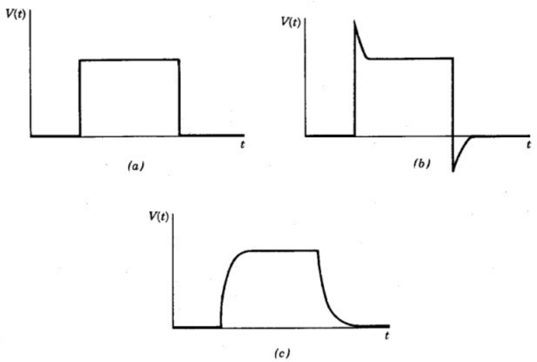


Figure 9.52 Waveforms from resistive voltage divider. (*a*) Ideal output voltage from a square-pulse input. (*b*) Output with significant shunt capacitance. (*c*) Output with significant series inductance.

High Frequency Voltage Dividers

- Most common alternatives
  - Capacitive divider
  - Balanced divider
    - Add capacitance to “swap” strays
    - Can be done with discrete components
    - Alt: physically divide resistive medium
      - Water
      - Thin film
    - Typical design of commercial HV probes
  - Inductive dividers used for dI/dt

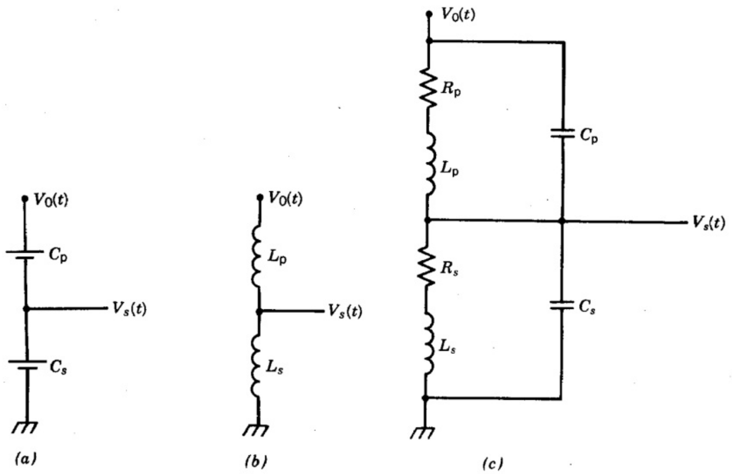


Figure 9.53 Voltage dividers. (*a*) Capacitive. (*b*) Inductive. (*c*) Balanced voltage divider.

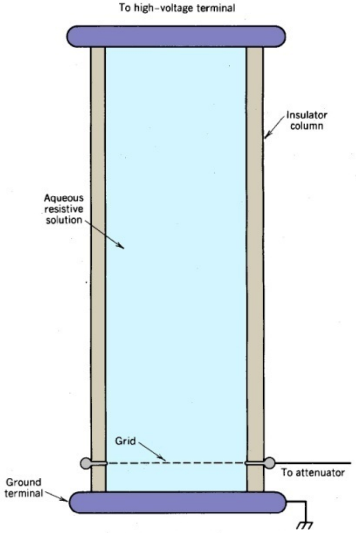


Figure 9.54 Balanced voltage divider with water solution resistor.

Scope Probes

- Balanced probes
  - Input impedance is frequency dependent
  - Scope impedance impacts response
- Bandwidth is limited
  - May be substantially less than rating, depending on ground connection
- HV versions require tuning to scope
- Pulsed power workhorses
  - P5100: 100X, 2.5 kV, 250 MHz
  - P6015: 1000X, 20 kV, 75 MHz
  - P5210 (differential): 5 kV, 50 MHz, 2 kV common-mode

Current Measurement

- Current viewing resistor
  - V = IR
- Time changing induced magnetic field, dB/dt
  - B-dot loop
    - V = NA dB/dt
      - Coil of area, A, with N turns
    - V = NAB/RC
      - Passive RC integrator
    - Calibration difficult, function of source and loop
      - Location
      - Size
      - Orientation
  - Rogowski coil
    - Encloses current source
    - Eliminates location/orientation calibration factors

Rogowski Coil

- Usual “air core” approximation, diamagnetic field of loop is negligible
  - $B_i = B$
- $B(r) = \mu I/2\pi\rho$
- $V = NA\, dB/dt$

  $= \mu A(N/2\pi\rho)\, dI/dt$

  $= \mu A(N/\ell)\, dI/dt$

  $= \mu A(N/\ell) I/RC$ (with RC integrator)

  ℓ is coil length

  N/ℓ is number of turns/meter
- Can be built in the lab
  - Calibration challenges: accurately measuring A and N/ℓ
  - Signal attenuation from passive RC integrator yields small signals unless I very large or time constant short
- Commercially available

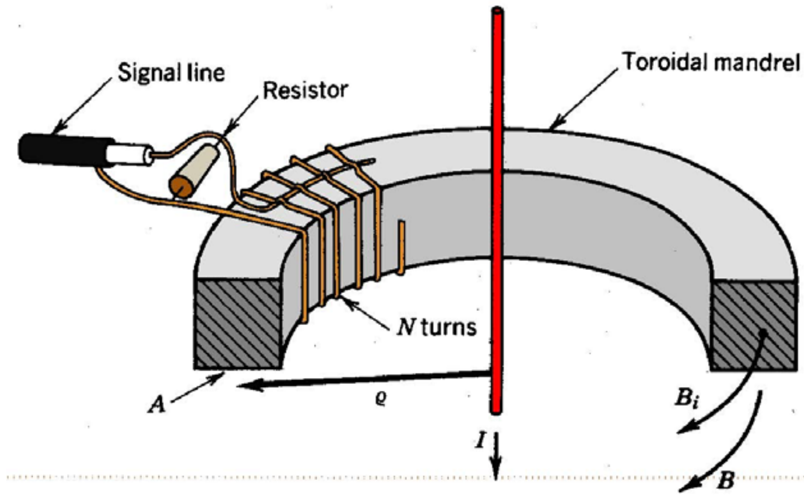


Figure 9.58 Rogowski loop—self-integrating current probe.

Self-integrating Rogowski

- More rigorously, the field B_i, in Fig 9.58

  $B_i = B - \mu i\,(N/2\pi\rho)$

  where i is the current flowing in the coil

  $i = NA\,(dB_i/dt)/R$

- Combining the above and solving for B

  $B = B_i + (dB_i/dt)\,(\mu N^2 A/2\pi\rho R)$

  $= B_i + (dB_i/dt)\,(L/R)$ inserting the identity for a solenoid inductor

- When the time constant L/R is large compared to the time scale of current variations: $(d/dt)\,(L/R) >> 1$, then the left term above can be neglected and:

  $B \approx (dB_i/dt)\,(\mu N^2 A/2\pi\rho R)$

- Recognizing $B = \mu I/2\pi\rho$ and solving for dB_i/dt as a function of coil current

  $i = I/N$

- Typically, L is made large by using a ferrite core
- Commercial current transformer