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Practical Probing Techniques for EMC Troubleshooting

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WPI SILENT Solutions for your noisy world. MISSOURI S&T UNIVERSITY OF OXFORD

Instructor Biography

Lee Hill is Founding Partner of SILENT Solutions LLC, an independent electromagnetic compatibility (EMC) and RF design firm he established in 1992. Besides providing EMC design review and troubleshooting services, Lee is also a member of adjunct faculty at Worcester Polytechnic Institute (WPI) where he teaches graduate courses in EMC. He is also an EMC class instructor at the University of Oxford (England), and for the IEEE EMC Society's annual Global University program and EMC Fundamentals workshop. In past years Lee was also an EMC course instructor for UC Berkeley Extension as well for Hewlett Packard and Agilent Technologies. Previously Lee was Principal EMC and Systems Engineer at Digital Equipment Corporation's Workstation Systems Engineering Group in Palo Alto, CA. In 2017 Lee founded SILENT Solutions GmbH in Munich, Germany.

Lee received the Master of Science Degree in Electrical Engineering & Electromagnetics with highest honors from the University of Missouri-Rolla, (now Missouri University of Science and Technology). He is an inventor of three US patents for EMI control in electronic systems, and provides expert witness services for patent litigation.

In the past fifteen years he has been a frequent featured speaker at IEEE EMC Society fundraising events in cities throughout the US including Santa Clara, Seattle, Portland, Chicago, Milwaukee, Dallas/Fort Worth and Detroit. He has also provided technical presentations to Society chapters in Los Angeles, San Diego, Santa Clara, Boston, Austin, Colorado Springs, Pittsburgh, and Orange County, CA. He served a term as an IEEE EMC Society Distinguished Lecturer from 1994-1996.

Lee has over twenty-five years of experience in the EMC design and retrofit of complex electronic systems. He has been teaching short courses on EMC design and troubleshooting for twenty years. Lee consults and teaches worldwide, and has presented classes in Taiwan, Singapore, Mexico, Norway, Canada, South Korea, France, Germany and United Kingdom. He has completed a three-year term on the Editorial Review Board of Printed Circuit Design Magazine.. He is an avid father, runner, motorcyclist, table tennis player and Amateur Radio operator, and has served as an officer on the board of directors of several non-profits.

Lee is past member of the IEEE EMC Society Board of Directors (2004-2007). From 1999-2006 he chaired the IEEE EMC Society's Distinguished Lecturer Program, and served as Co-Technical Chair of the 2003 IEEE Symposium on EMC in Boston, MA. In 1999 Lee received a Certificate of Appreciation from the EMC Society for significant contributions to education through his annual participation in the Demonstrations and Experiments portion of annual IEEE EMC Symposia.

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Thank You!   Free Bonus Technical Presentation Available

Dear Demystifying EMC 2020 Attendee:

Randal and I would like to thank you again for taking time out from work to attend Lee's presentation(s) this year.

Please let us know if you would like to bring a SILENT EMC course to your work location. We offer intensive two, three, and four day format EMC courses for electrical hardware designers, PCB designers, mechanical engineers, and EMC engineers.

We have delivered these courses around the world to companies that develop a wide variety of electronic products and systems.
If you would like to receive a free bonus technical presentation from SILENT, please just follow this link, Bonus Presentation
then enter your name and email, and we'll send you an updated pdf copy of Lee's very popular talk
"Mastering the Details of EMI Suppression Ferrites."

This bonus presentation discusses the performance characteristics and high frequency EMI suppression ferrites and important considerations for practical applications. When this talk is given live, Lee includes a hardoware demonstration of the effect of DC bias on a ferrite's impedance, using a network analyzer, power supply, and bias network. Lee has given this presentation throughout the US, Germany, and at DeMystifying EMC 2019 at Silverstone in the UK.

Warm Regards,

Lee Hill

Randal Vaughn

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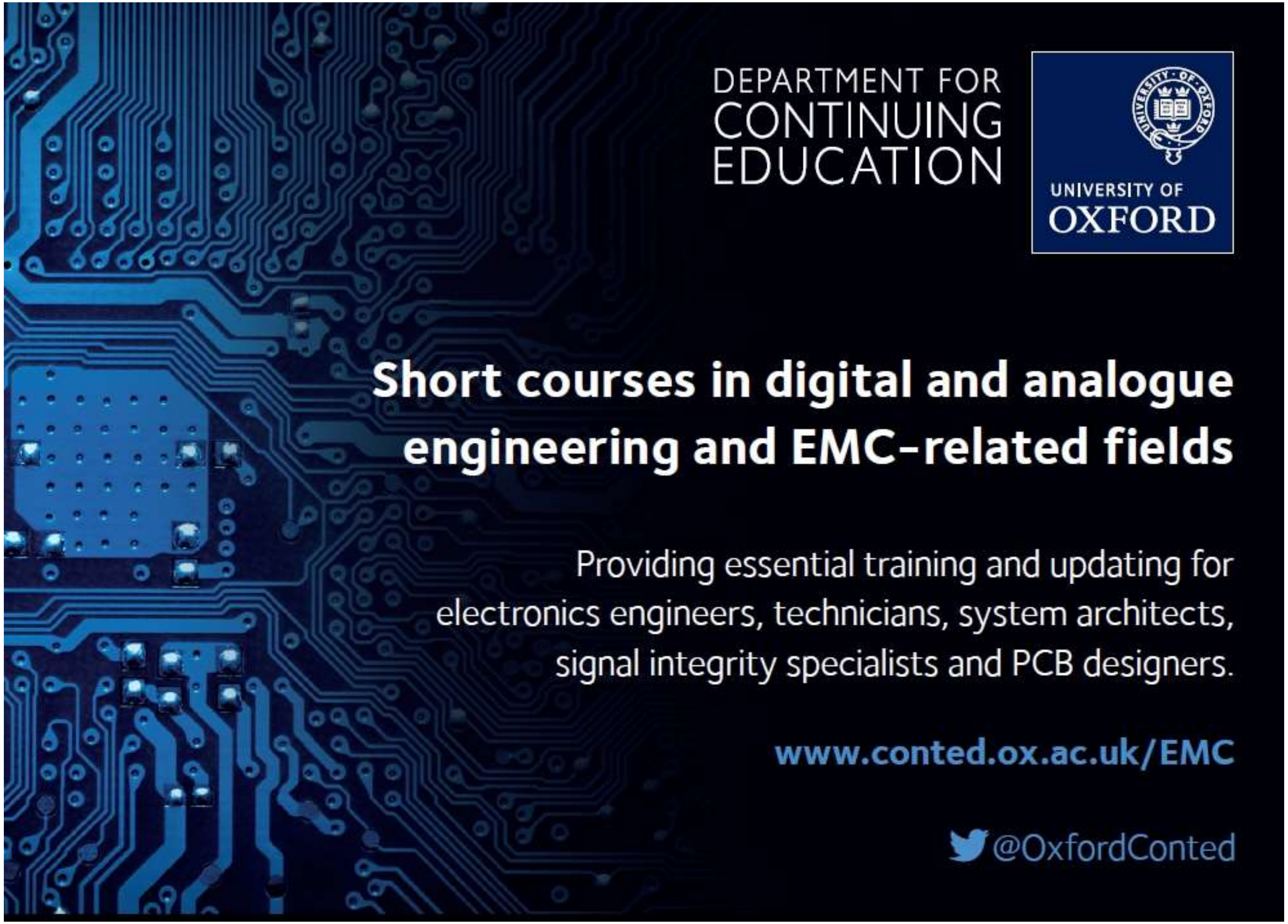
SILENT Training Events - Europe 2020

Please get in touch and visit with me if you are traveling to one of these cities in 2020
Find more info at www.silent-solutions.com

EMV, Cologne, Germany	***March 2020***
Posnań, Poland	***May 5-9, 2020***
University of Oxford, England	***June 2020***
IEEE Symposium on EMC, SI+PI	***July 2020 (Reno, Nevada)***
SILENT EMC Courses	***May, October 2020 (Boston, Silicon Valley)***
Dresden, Germany	***October 2020***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Short courses in digital and analogue engineering and EMC-related fields
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2020 summer courses

HIGH-SPEED DIGITAL, ANALOGUE AND EMC ENGINEERING

Applying Practical EMI Design and Troubleshooting Techniques
9 – 10 JUNE
Tutor: Lee Hill, SILENT Solutions LLC & GmbH, USA & Germany

Advanced Printed Circuit Board Design for EMI & Signal Integrity
9 AND 11 JUNE
Tutor: Lee Hill, SILENT Solutions LLC & GmbH, USA & Germany

Mechanical Design for EMC
9 AND 12 JUNE
Tutor: Lee Hill, SILENT Solutions LLC & GmbH, USA & Germany

Mastering High Speed Serial I/O Technology
22 – 24 JUNE
Tutor: Ransom Stephens, Signal Integrity Specialist

Resetting Your Signal Integrity Knowledge
24 – 26 JUNE
Tutor: Dr Istvan Novak, Senior Principal Engineer, Oracle

Making Successful Power Distribution Designs
29 JUNE – 1 JULY
Tutor: Dr Istvan Novak, Senior Principal Engineer, Oracle

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SILENT Solutions LLC & GmbH, Since 1992

Amherst,
New Hampshire

Boston, Massachusetts

1992
Silicon
Valley

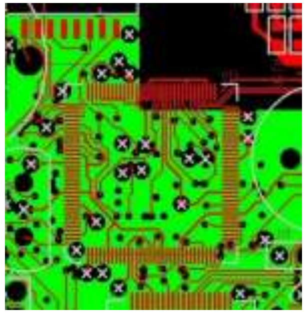
Founded 2017
Munich

Electrical engineering consulting

Expertise in preventing & solving electrical noise problems in hardware

- ***Regulatory,*** **“compliance”** issues
- ***Functional,*** **“self-interference”** problems

What Do We Do?



DESIGN REVIEWS

TROUBLESHOOTING

TRAINING

Wireless Link Issues

Electrostatic Discharge

Self Interference

RF Design

Conducted & Radiated Immunity

Signal Integrity

Conducted & Radiated Emissions

RF Immunity

Outline - Let's Talk about EMC Probes

- Why are we using probes?
- Why CURRENT is important in typical regulatory noise problems
- Key PASSIVE Probe Characteristics
- Voltage Probes
- Clamp-on Current Probes
- Magnetic Field Probes
- Electric Field Probes
- Self-contained Immunity Generator "active probes"
- Our Favorite Tools

Special Thanks to Dr. Tom Van Doren, Professor Emeritus, Electrical and Computer Engineering Department, Missouri University of Science & Technology, for permission to use portions of his original source material in this section

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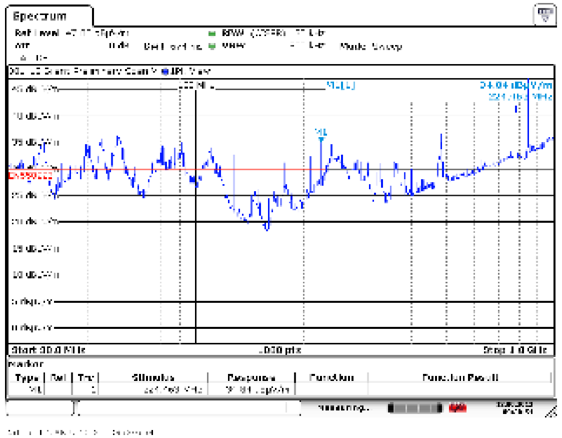
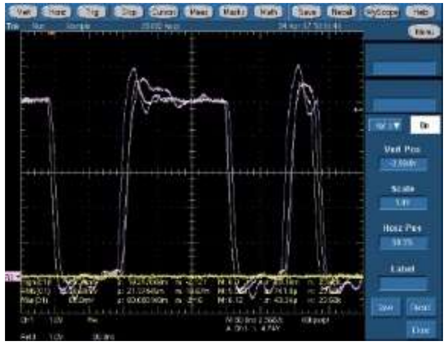
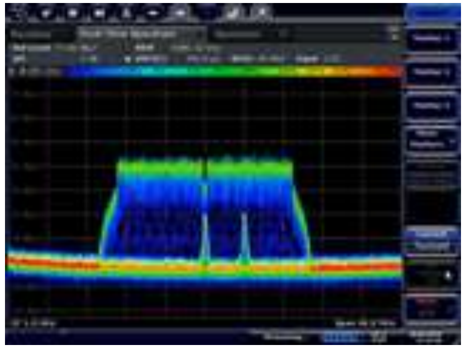
WHY Do We Use PROBES?



Find and solve a problem that causes EMC regulatory test failure



Find and solve a “functional” noise problem

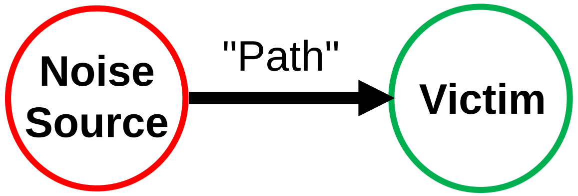


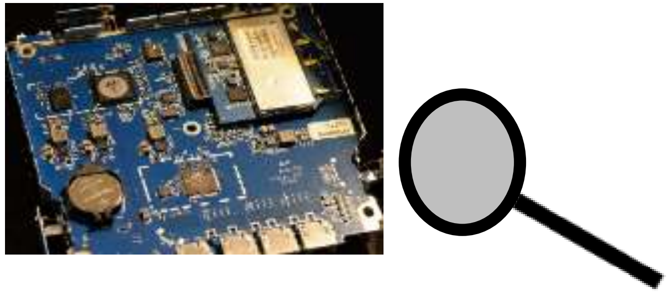
Characterize an environment

Characterize a device

WHAT Are We Trying To Do With A Probe?

Every noise problem is source – path – victim





<u>USE PROBES TO:</u>

LISTEN / FIND / MEASURE

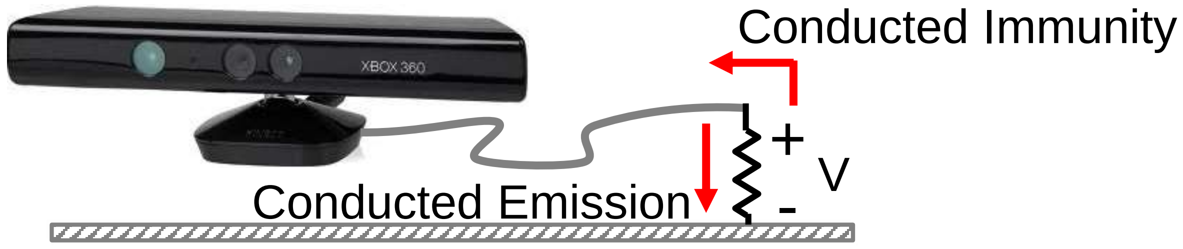
a noise quantity FROM an existing source

INDUCE / REPRODUCE

a noise quantity INTO an existing victim

Some probes are good at doing both, some probes are good for only one.

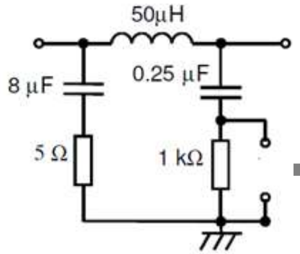
Most "Conducted" Noise Problems Can Be Understood by Locating the Path of the Responsible Noise Current



Conducted EMISSIONS

EUT Noise Current

LISN



Measured Noise Voltage

Conducted IMMUNITY

Current driven into EUT Cale

Noise Generator Current

INJECTION Probe

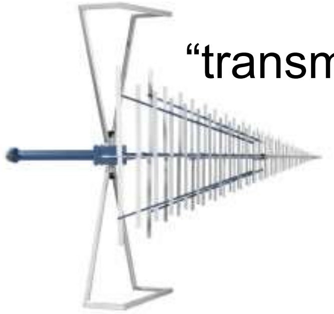
Most "Radiated" Noise Problems Can Be Understood by Locating the Path of the Antenna (noise) Current

Radiated Immunity

Radiated Emission

Radiated EMISSIONS

Current di/dt

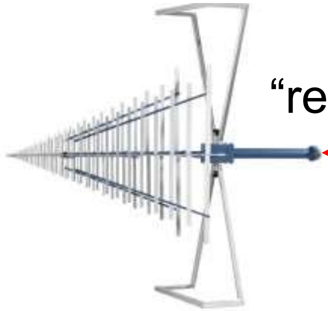


"transmitting"

Radio Wave E,H

Radiated IMMUNITY

Current di/dt



"receiving"

Radio Wave E,H

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What Makes a Good EMC Probe?

Bandwidth: $F_1 < \text{Frequency} < F_2$

Sensitivity (Listening), **Efficiency** (Injecting)

Less preamplifier gain (listening)
Less power amplifier gain (injecting)

Ruggedness

Usually the difference between purchased and homemade

Impedance **Loading** (of circuit under test)

Does the probe disturb the (I,V) quantity being measured?

Field Perturbation

Does the probe disturb the field quantity being measured?

Impedance Balance

When trying to measure Idm or Vdm, does Icm increase?

Repeatable Positioning

Same location = same E,H, same V,I

Cost, Calibration

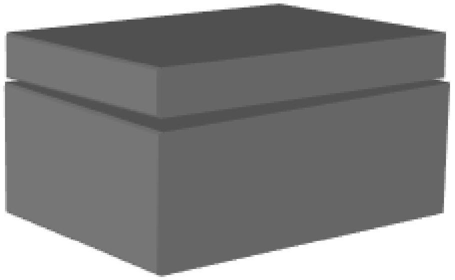
What Should We Try to Measure with Our Probe?

Coupling Mechanism	Quantity Measured	Measuring Process

Passive Voltage Probes (Listening to locate sources)

Measurements:

- Voltage across seams or apertures of conductive chassis
- Voltage between connector pin and conductive chassis

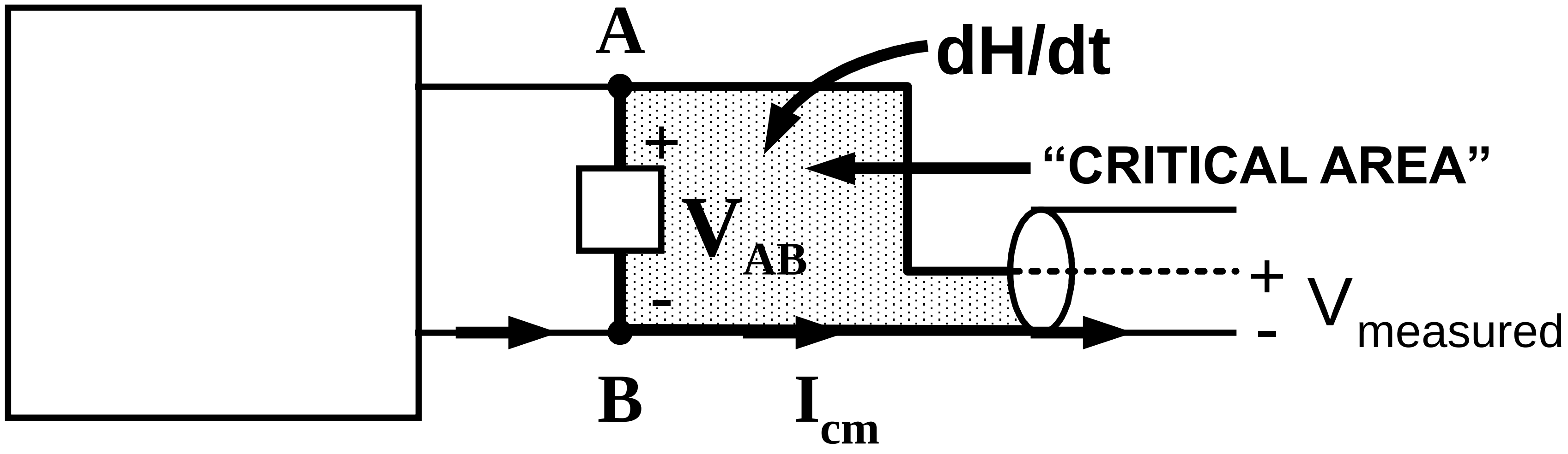


Applications

- Radiated or conducted emissions or self-interference
- Finding circuit nodes with “Bonus Noise” (Unexpected RF sources)
- Radiated emissions or self-interference in radio / “wireless” receivers

Problems with Passive Voltage Probes (Listening)

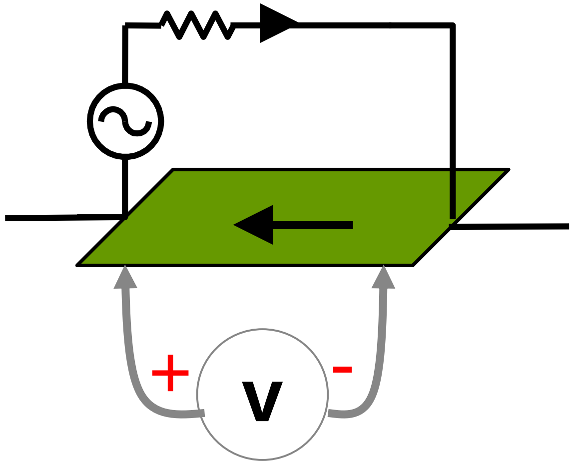
Sources of Measurement Error:



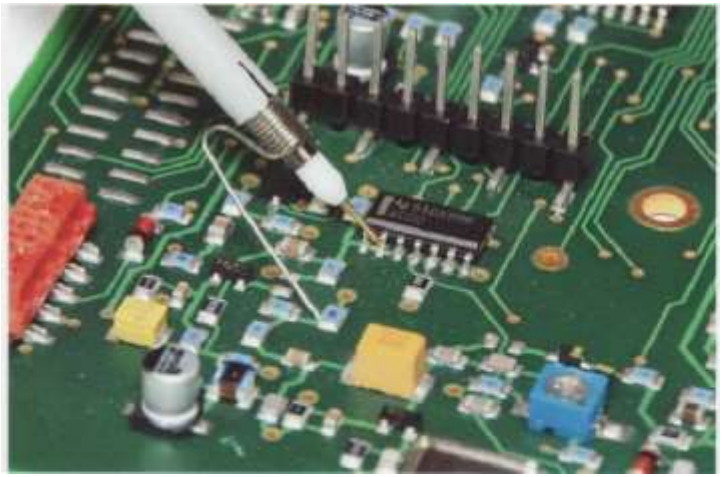
$$|V_{measured}| = V_{AB} \pm \omega_1 M I_{CM} \pm \omega_2 \iint H \cdot ds$$

You Can't Measure "Noisy Ground" or "Ground Plane Inductance or Voltage", or Voltage near Big $\bar{H}$ or Big I_{cm}

Sources of Measurement Error:



V depends on location of wires
and amount of flux wrapping the plane



"Critical Area"
is obvious

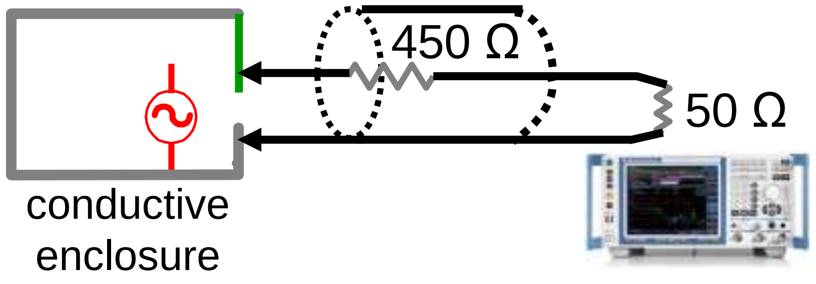
Passive, Unbalanced 10x Voltage Probes

(Listening to locate noise sources)

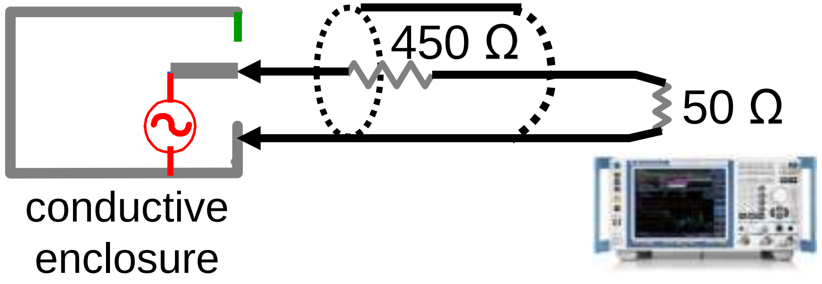
Radiated emissions

- Measure voltage across seams or apertures of a conductive chassis
- Measure voltage between a connector pin and a conductive chassis

Aperture



Connector Pin



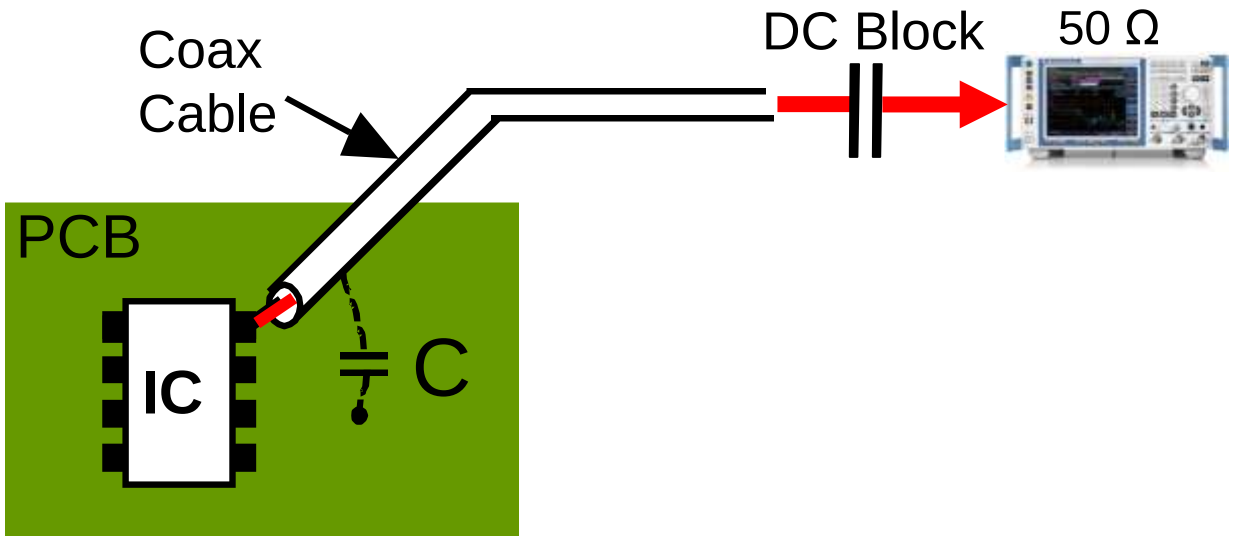
Measuring voltage difference across many different seams or pins might identify the location of a dominant energy leakage

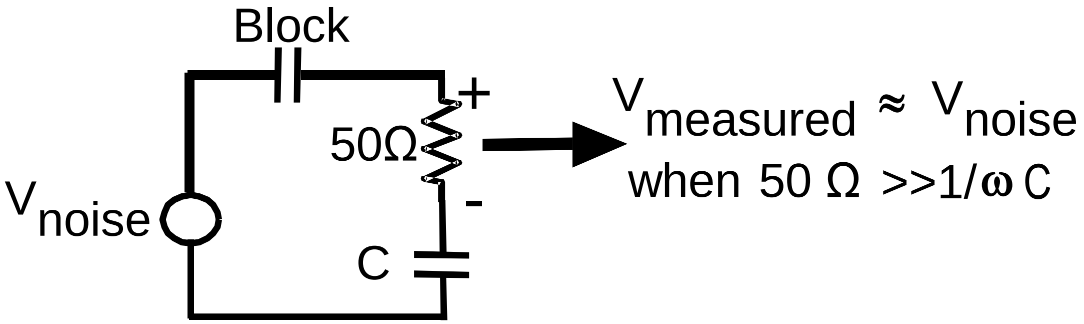
Passive "1 Terminal" Voltage Probes

Radiated Emissions or E field Source (dv/dt) :

Finding Circuit Nodes with "Bonus Noise"   (Unexpected RF sources)

E field source (dv/dt) – cause of radiated emissions if coupled to an antenna

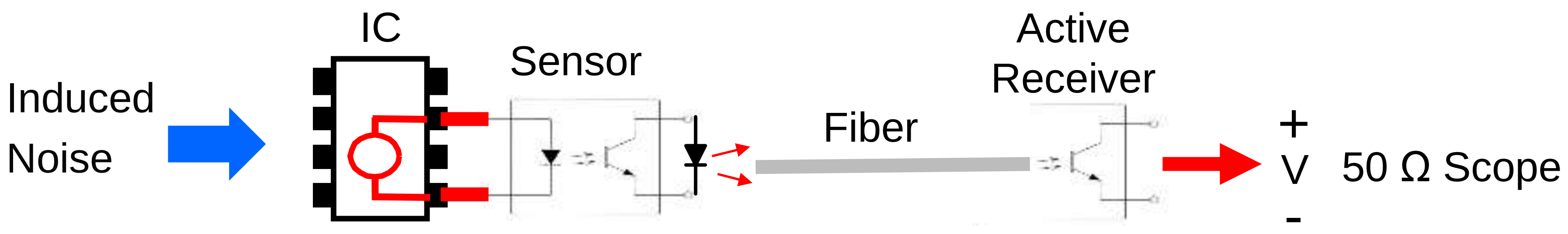




Active Voltage Probes (Listening to SIGNAL during NOISE Event)

Fiber optic analog or digital signal detector, hardened against RF, monitors critical EUT signal via fiber to active receiver.

For use during conducted immunity or radiated immunity or ESD tests.
Measure health of intended signals with isolated sensor to avoid RF coupling via measurement wires.

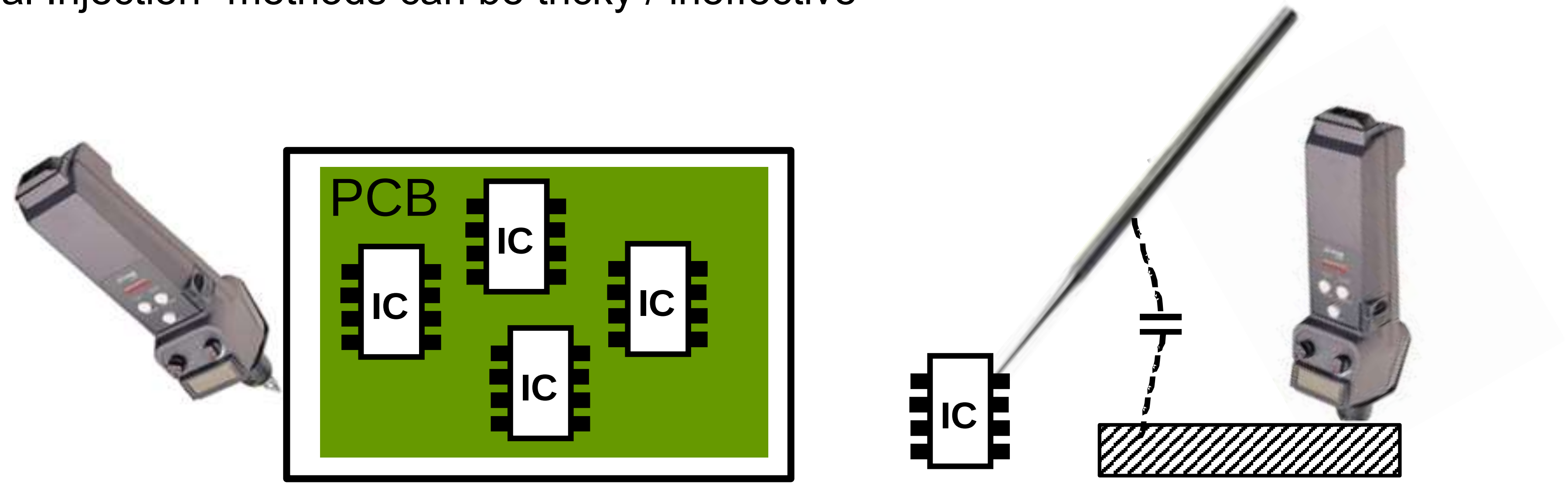


Active Noise Probes (Generators) To Locate Victim Circuits That are Sensitive to ESD, EFT, Radiated Immunity

Identifying the precise location of victim circuits that cause system level ESD failure

Which IC / trace causes system ESD failure?

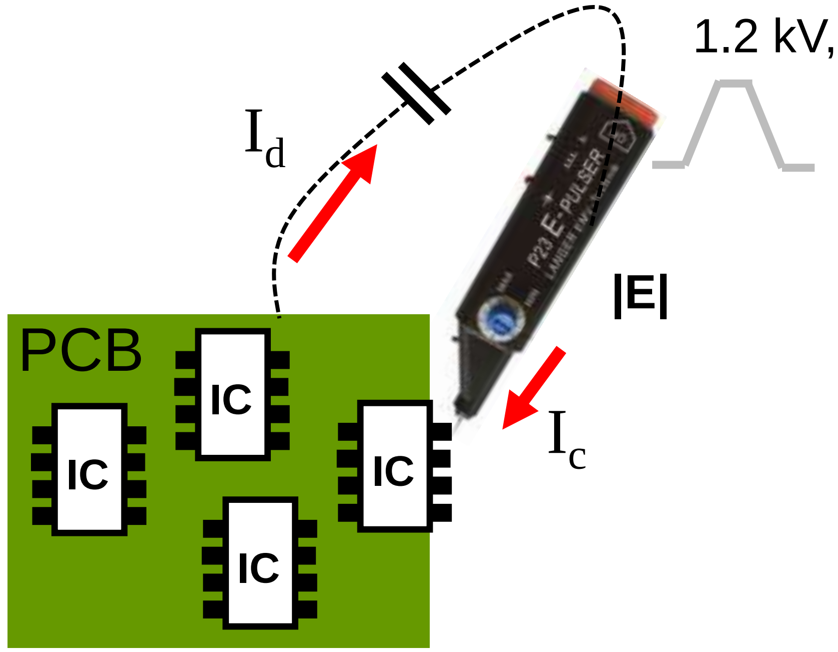
“Manual Injection” methods can be tricky / ineffective

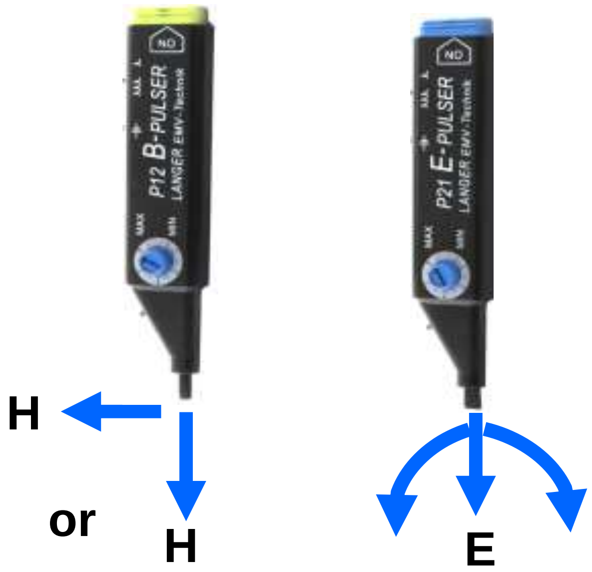


Active Noise Probes (Generators) To Locate Victim Circuits That are Sensitive to ESD. EFT, Radiated Immunity

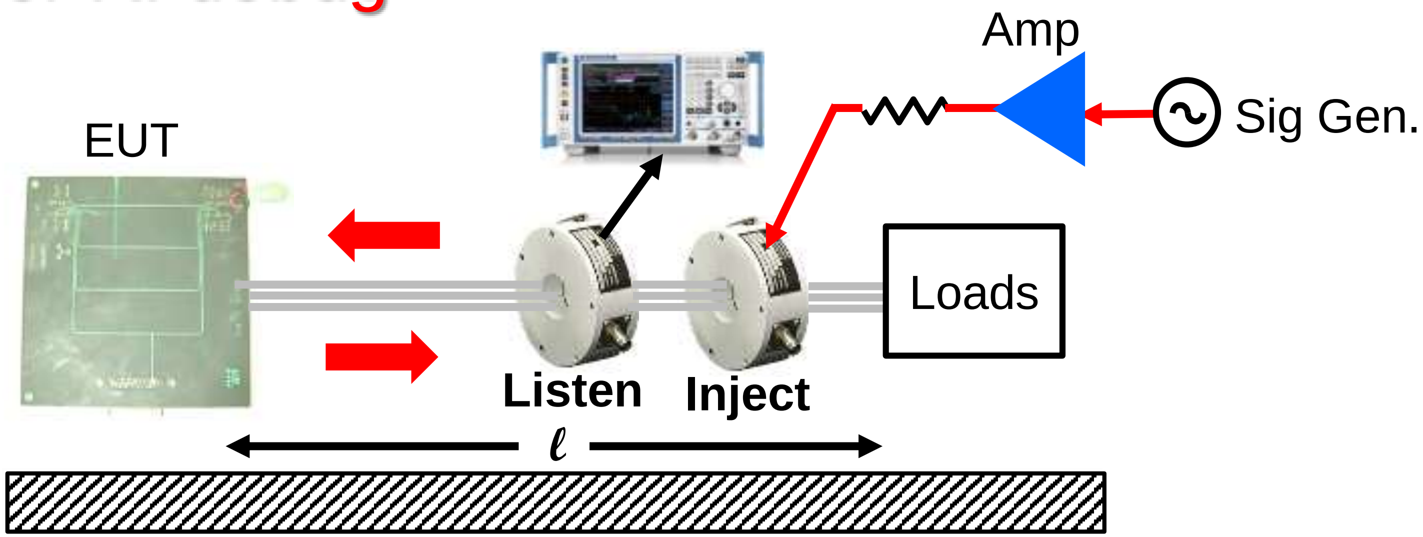
Identifying the precise location of victim circuits that cause system level ESD failure

1.2 kV, 1.8 nsec min. edgetime, single event or 5 kHz pulse train





Passive Current Probes - Listening for CE or RE, Injecting for CI or RI debug



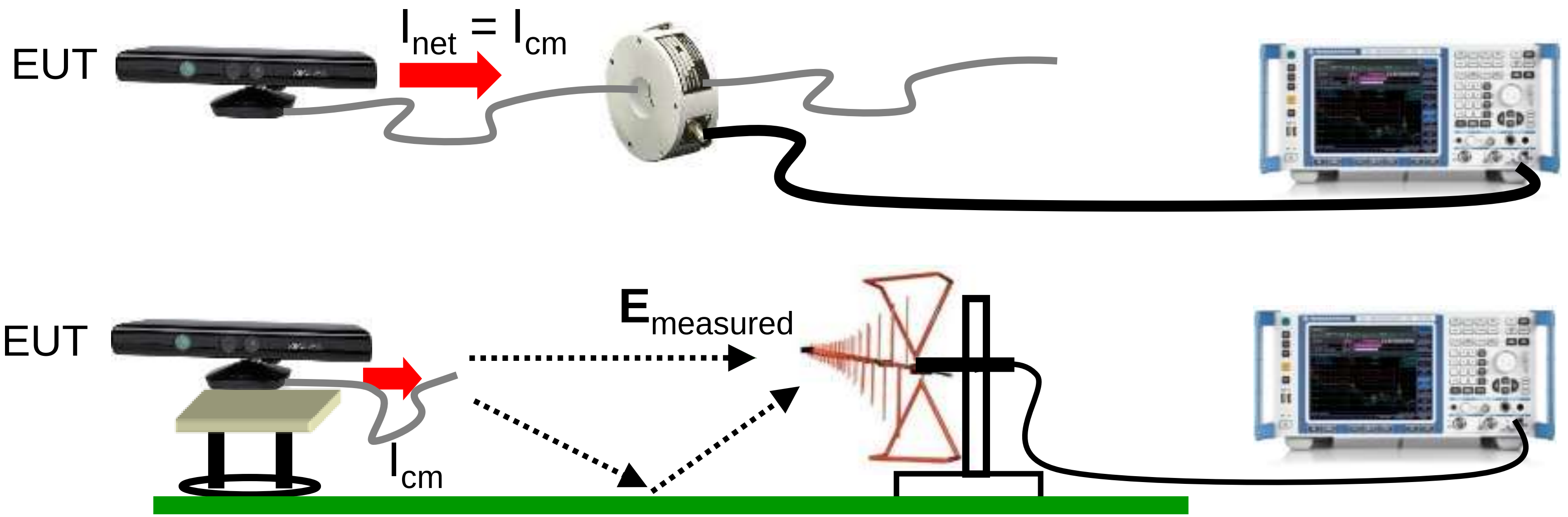
Shielded – We only want to detect dH/dt and thus the current (listening)

We only want to deliver i(t) (injecting)

Net current Enclosed = $\oint \mathbf{H} \bullet dl = \underbrace{\oint \mathbf{J} \bullet \mathbf{dS}}_{\text{conduction}} + \underbrace{\cancel{\frac{d}{dt}\int \mathbf{D} \bullet \mathbf{dS}}}_{\text{displacement}}$

Probe with Electric Field shield makes this term = 0

Passive Current Probes (Measuring Icm that cause RE)



Under far field conditions, at a distance of R meters from a λ/2 dipole

$E = \frac{60\, I}{R}$ where I = current (A) at center of dipole

$I < \frac{R\,|Emax|}{60} = \frac{(10m)(100\ \mu V/m)}{60\ \Omega}\ /\ 2 \sim \boxed{8\ \mu A}$ (EN 55032 @ 10m)

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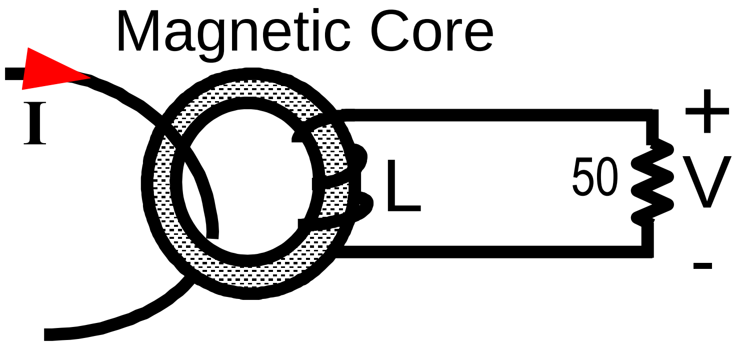
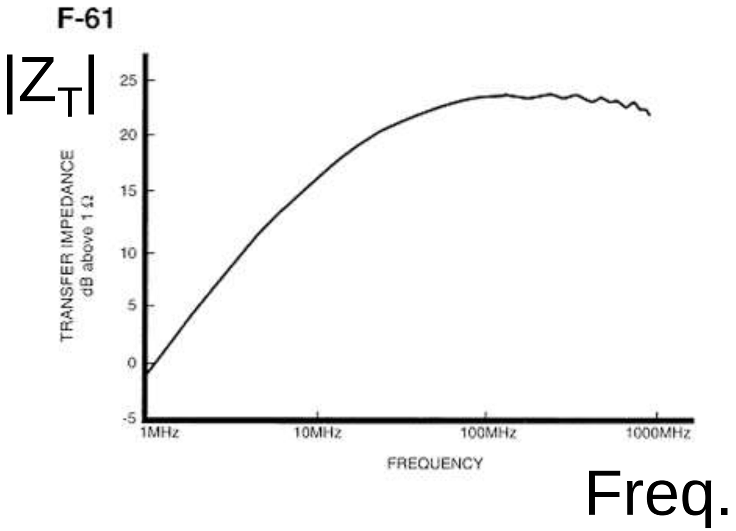
Passive Current Probes (Listening for CE or RE)



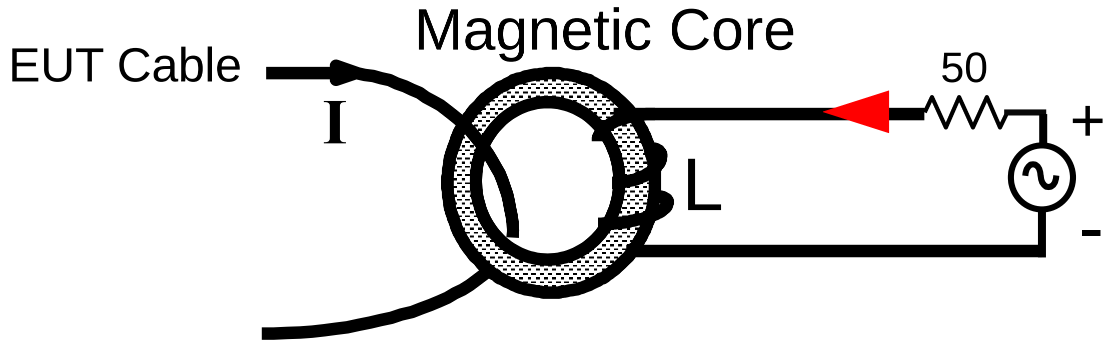
$|I| = |V| / |Z_T|$ $V_{dB} = I_{dB} + Z_{T\ dB}$



For listening to noise current, we want a "sensitive" probe that delivers BIG voltage output for a given I_{noise} so we want Z_T to be ___.

Do you like 0 dBΩ probe?

Passive Current Probes - <u>Injecting Icm</u> for CI or RI debug

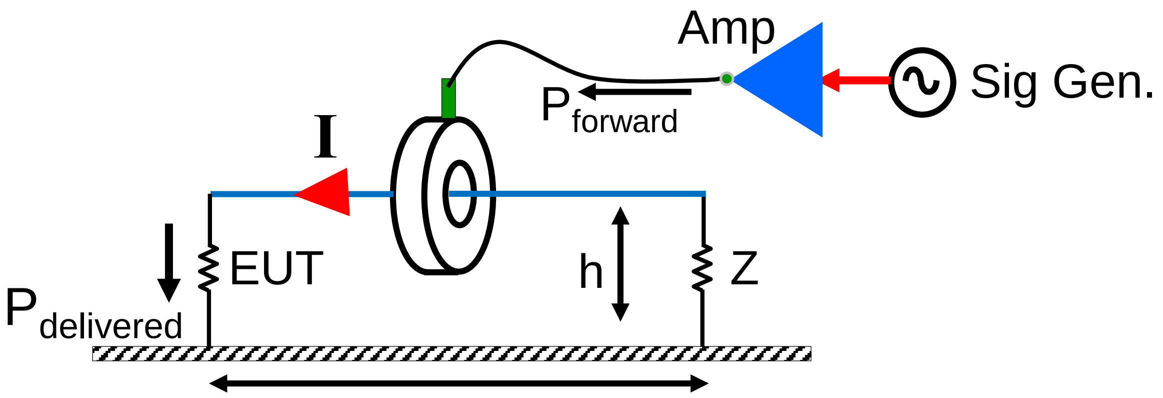


For a given available RF power output, we want a probe that delivers maximum current I

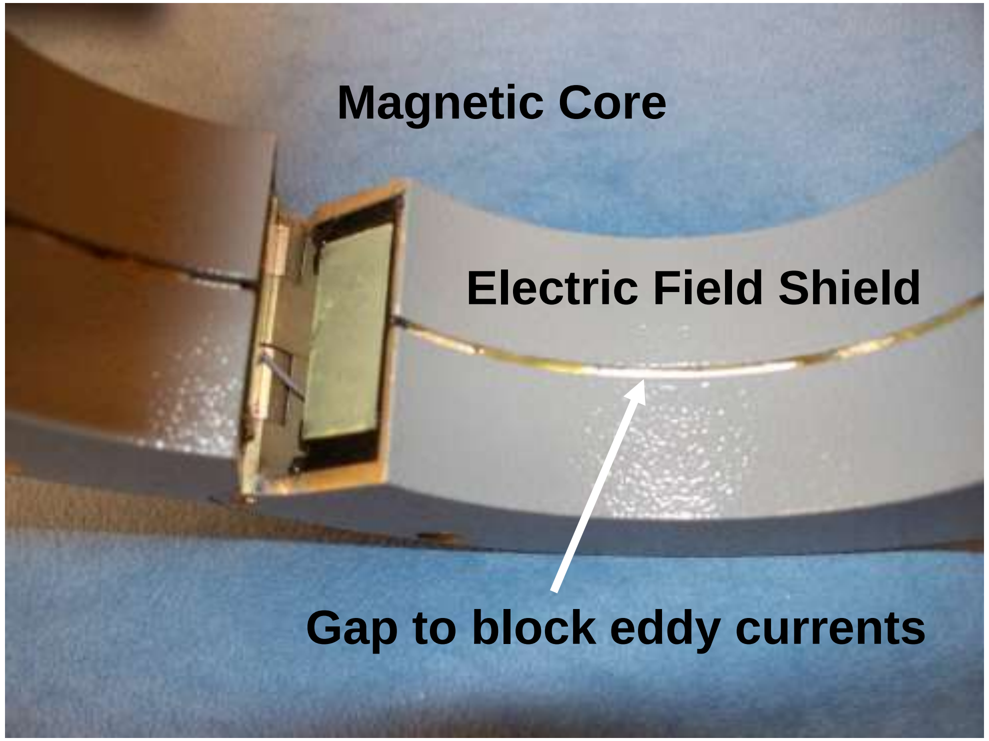
"Insertion Loss" Calibration

10 Log ($P_{forward}$ / $P_{delivered}$)

<u>SMALL Insertion Loss = Good</u>



Passive Current Probes – Electric Field Shielding



The wire under test can capacitively couple to the probe winding through the slot This is usually minor at F< ~ 400 MHz.

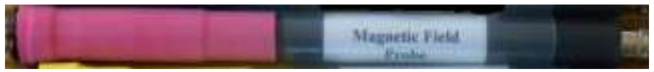
Some people use a foam “donut” to prevent cables from getting very close to the gap, which can cause loading and measurement repeatability problems.

Passive Magnetic Field Probes

We measuring **B**, to find **I** (magnitude & direction)
Where is the magnetic flux?

Large probes for large objects – cables, connectors, enclosures

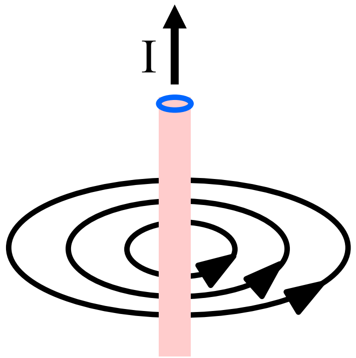
1 cm (and larger) loops



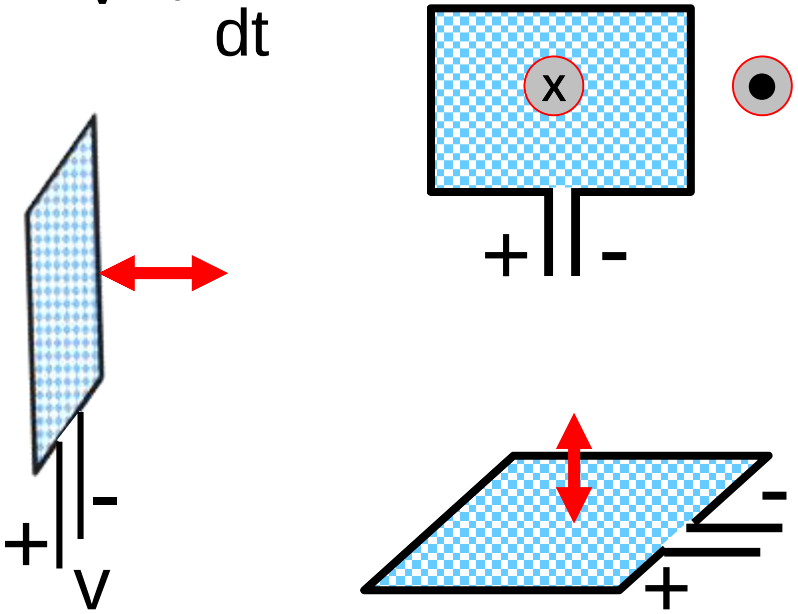
> 1 cm aperture

Passive Magnetic H Field Probes (Listening for CE or RE, or Injecting H)

$$\oint \mathbf{H} \bullet dl = \underbrace{\oint \mathbf{J} \bullet \mathbf{dS}}_{\text{conduction}}$$



$$V \propto \frac{dH}{dt}$$



We can use a simple loop probe to:

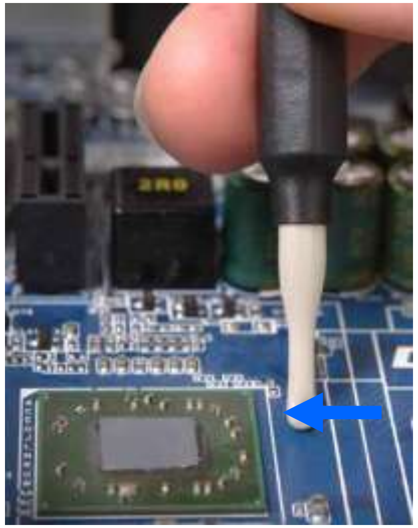
1) Detect the relative amplitude AND direction of time-changing current (nice if it's calibrated). Loop output = 0 when loop vector is <u>parallel</u> to direction of current
Loop output = maximum when loop vector is <u>perpendicular</u> to direction of current

2) Detect the relative amplitude of a time changing magnetic field e.g., if we're failing a magnetic field emissions test or looking for "leaky" inductive components.

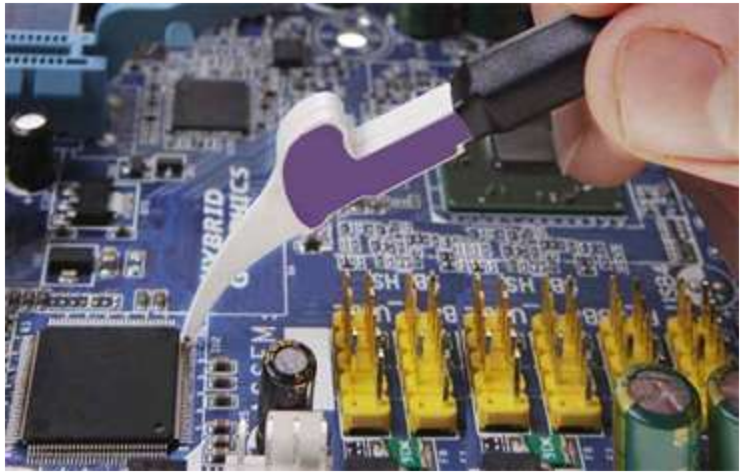
Passive & Active Magnetic Field Probes

Small probes for small objects – PCBs, ICs, PCB traces, PCB vias

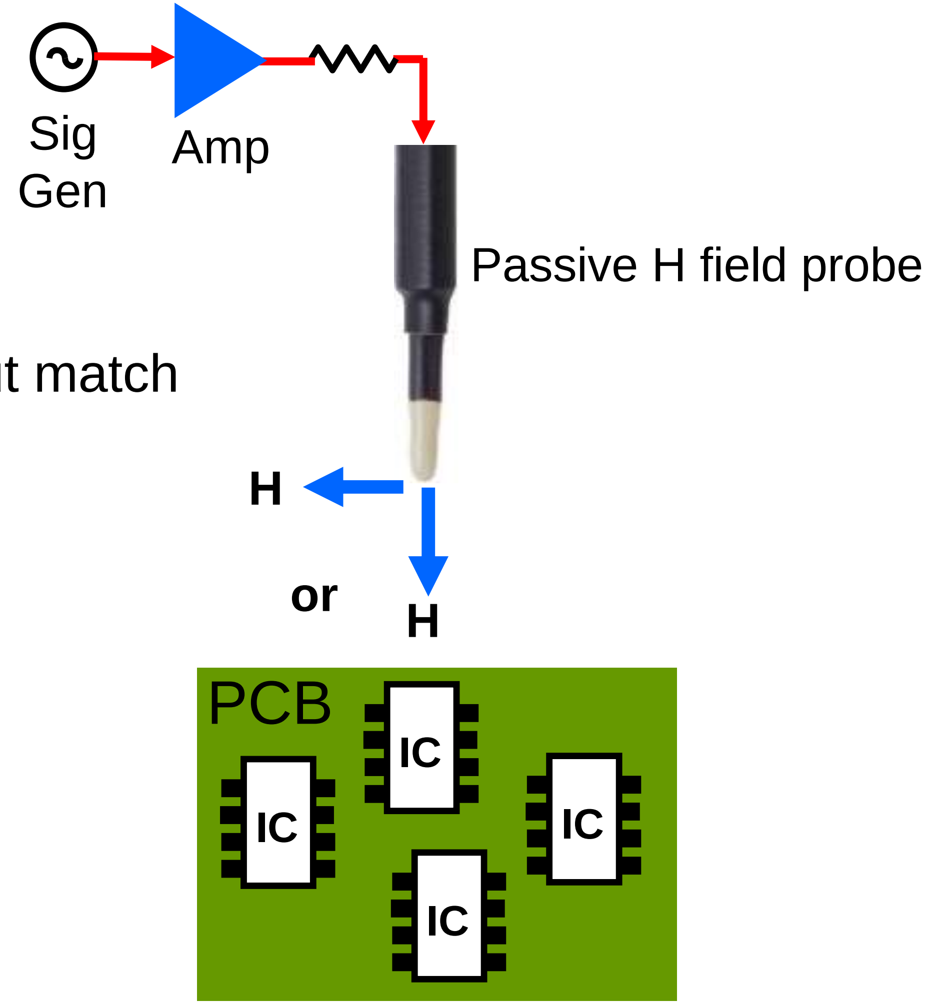
Passive
Calibrated. 1 GHz ≤ F ≤ 10 GHz
Resolution ~ 1 to 2 mm



Active: These can localize noise to a via or BGA bump.
Calibrated. 100 MHz ≤ F ≤ 10 GHz
Resolution ~ 200 um

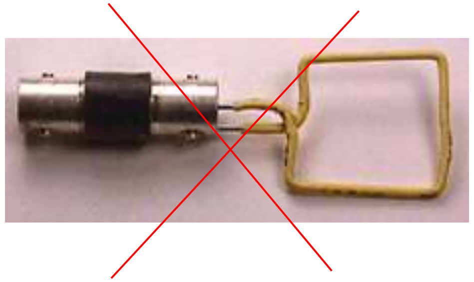


Use Passive H field Probes for Immunity Troubleshooting



Some vendors categorize
max forward power and input match

Pitfalls of Homemade Probes



H field loop probes and current probes must be shielded, otherwise;

- Confusing measurement results
  - May interact with human's capacitance
  - May interact with E, dv/dt of circuit under test
- Poor spatial resolution – It's tough to make really tiny, shielded, homemade H field probes.

Homemade probes are often uncalibrated

- Difficult to distinguish between "interesting" and "important" when multiple sources exist.
- Large bandwidth of commercial probes is difficult to duplicate

Common Mistakes When Using EMC Probes

- Using too much (preamplifier) gain with 1cm or larger H field loop probes.
- Using homemade H field probes with poor E field shielding
- Trying to fix radiated emissions problems by measuring and "fixing" near H and E fields from PCBs, instead of measuring I_{cm} from cables and V_{cm} along enclosure seams
- Trying to measure voltages between different "GNDs"….
  - a) with large measurement loop area
  - b) in areas with large dB/dt

Summary of Key Points

- **Use probes to find and mesure, OR inject Icm, common-mode current**

- **For best troubleshooting, know how to choose correct probe with best characterisics**

- **Be able to interpret vector imformation about noise you are measuring**
  - **To distinguish between "interesting" and "important", know how "big is bad"**
  - **To distinguish vector direction of noise current or field, understand how your probe works**

Thank you! Questions?

Please get in touch and visit with me if you are traveling to one of these cities in 2020

EMV, Cologne, Germany	***March 2020***
Posnán, Poland	***May 5-9, 2020***
University of Oxford, England	***June 2020***
IEEE Symposium on EMC, SI+PI	***July 2020 (Reno, Nevada)***
SILENT EMC Courses	***May, October 2020 (Boston, Silicon Valley)***
Dresden, Germany	***October 2020***

Where to Buy the Tools

Places to buy the tools that SILENT uses:

Real-Time EMC Spectrum Analyzers and Test Receivers

Rohde & Schwarz	www.rohde-schwarz.com

Handheld E & H Probes, Noise Generators

Langer EMV-Technik	www.langer-emv.com
Van Doren Company	www.emc-education.com

Clamp-on Current Probes

Fischer Custom Communications	www.fischercc.com

SILENT's Favorite Passive Current Probes

Fischer F-61

Listening

1 MHz ≤ F ≤ 1 GHz

Fischer F-16

Listening

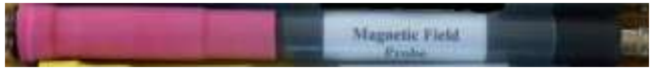
10 Hz ≤ F ≤ 70 MHz

Fischer F-130x

Injection

10 kHz ≤ F ≤ 400 MHz

SILENT's Favorite Passive Near Field E + H Probes



Van Doren Company
MFH-23
MLF-11
40 MHz ≤ F ≤ 400 MHz
3 kHz ≤ F ≤ 300 kHz

ETS-Lindgren
1 and 3 cm loop probes
F ≤ 1.5 or 2.3 GHz

Langer EMV-Technik
RF-R400-1
RF-E 02
RF-E-10
RF-U 2.5-2
RF-B 3-2
F ≤ 6 GHz
Best Spatial Resolution

Rohde & Schwarz
HZ-15 Probe Set

Probing of Systems / Cables

Probing of PCBs/ ICs

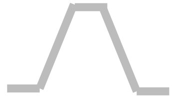
SILENT

SILENT's Favorite "Active" E + H Probes

All Made By Langer EMV-Technik

"Pulsers": P1 set, P23

Noise Generators



MFA Active H Field Probes

For Listening

SILENT

Practical Probing Techniques for EMC Troubleshooting

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EMC Course Instructor **University of Oxford,** England

Solutions for your noisy world.