Electromagnetic Emission from ‘Dielectric’ Optical Fiber Cables

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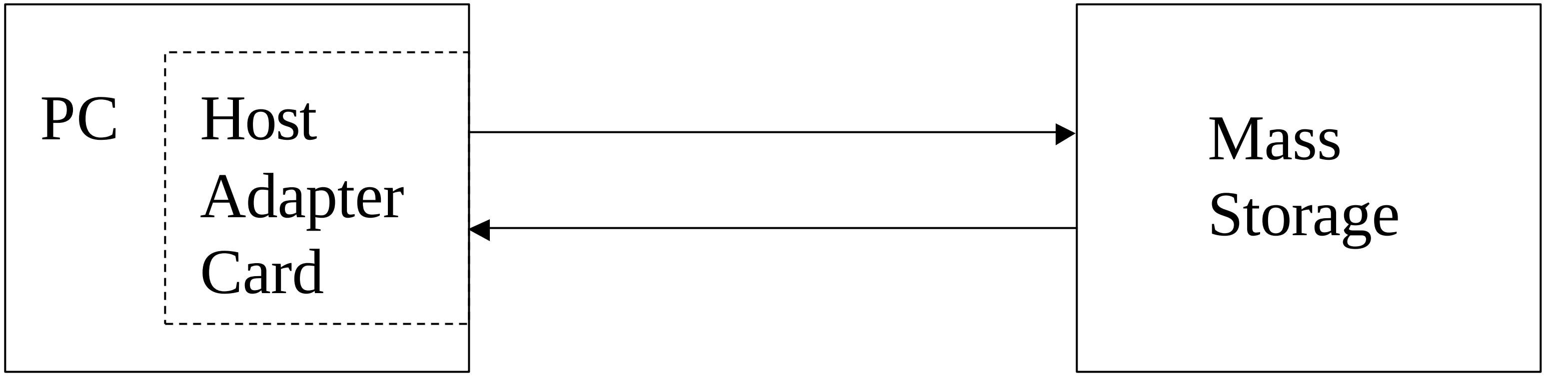
Outline

- Introduction
- Review of enclosure design rules
- Early emissions failures
- Proposed model
- Experimental Verification
  - Verify dipole radiation pattern
  - Verify driving source of dipole
  - Role of ground pins
- Conclusions

Electromagnetic Compliance (EMC)

- Nearly all equipment introduced into commerce must meet government Electromagnetic Compliance (EMC) regulations: FCC in the USA, IEC in Europe, Nemko in Scandinavia…
- Early optical fiber networking equipment - telecom apps:
  - Lower data rates (at first), installed and operated by trained personnel
  - Engineered installations, controlled access to equipment
  - Telecom typically FCC “Class A” requirement for RF emissions
- In 1990s networking technology proliferates - datacom apps:
  - Technology progressed to gigabit rates by the time low costs achieved
  - Plug-and-play installations, consumer and office environment
  - Datacom typically FCC “Class B” (more restrictive) for RF emissions
- EMI FAILURES IN EARLY DATACOM SYSTEMS
- In 2000s convergence and harmonization of requirements

Example: Point-to-Point Datacom Network

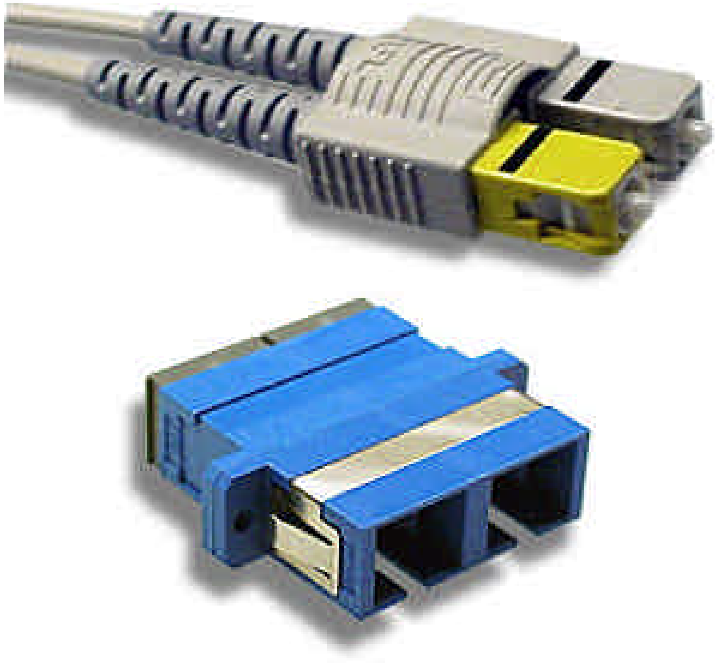


- Mass storage physically decoupled from CPU
- Tower, desktop, rack-mount, or “pizza-box” enclosures
- Enclosures always electrically shielded with limited apertures
- Optical fiber is medium of choice for high-speed data links
- Host adapter card (HAC) using e.g. PCI, ISA, S-Bus interface
- Interface with optical fiber via optical module on HAC
- Fiber-optic receptacle/connector protrudes through panel

Fiber-Optic Connectors and Receptacles

- Many types of fiber-optic connectors are in use
- Examples below are used in Telecom and Datacom

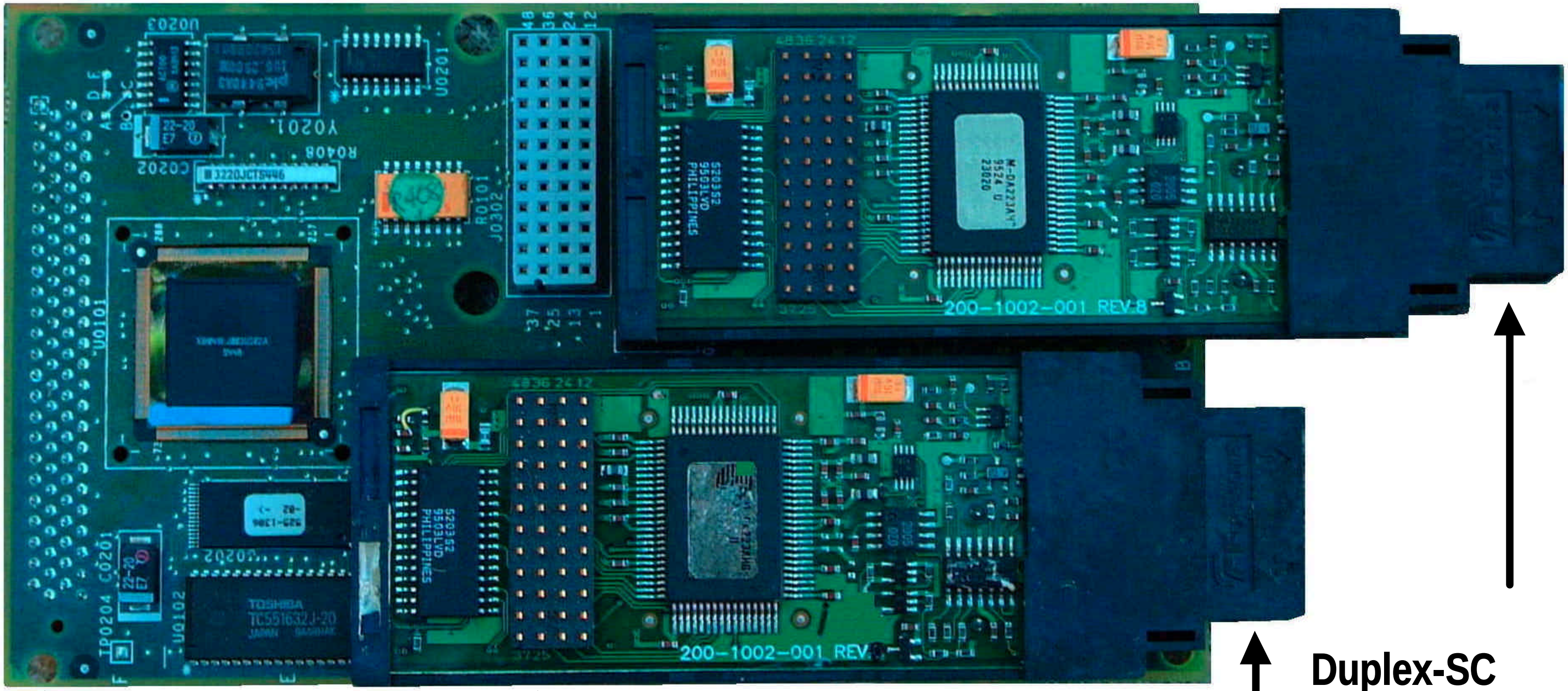
Simplex-SC



Duplex-SC

Photograph of HAC with optical modules

Enclosure not shown



Host Adapter Card (HAC)

48-pin Receptacle on HAC

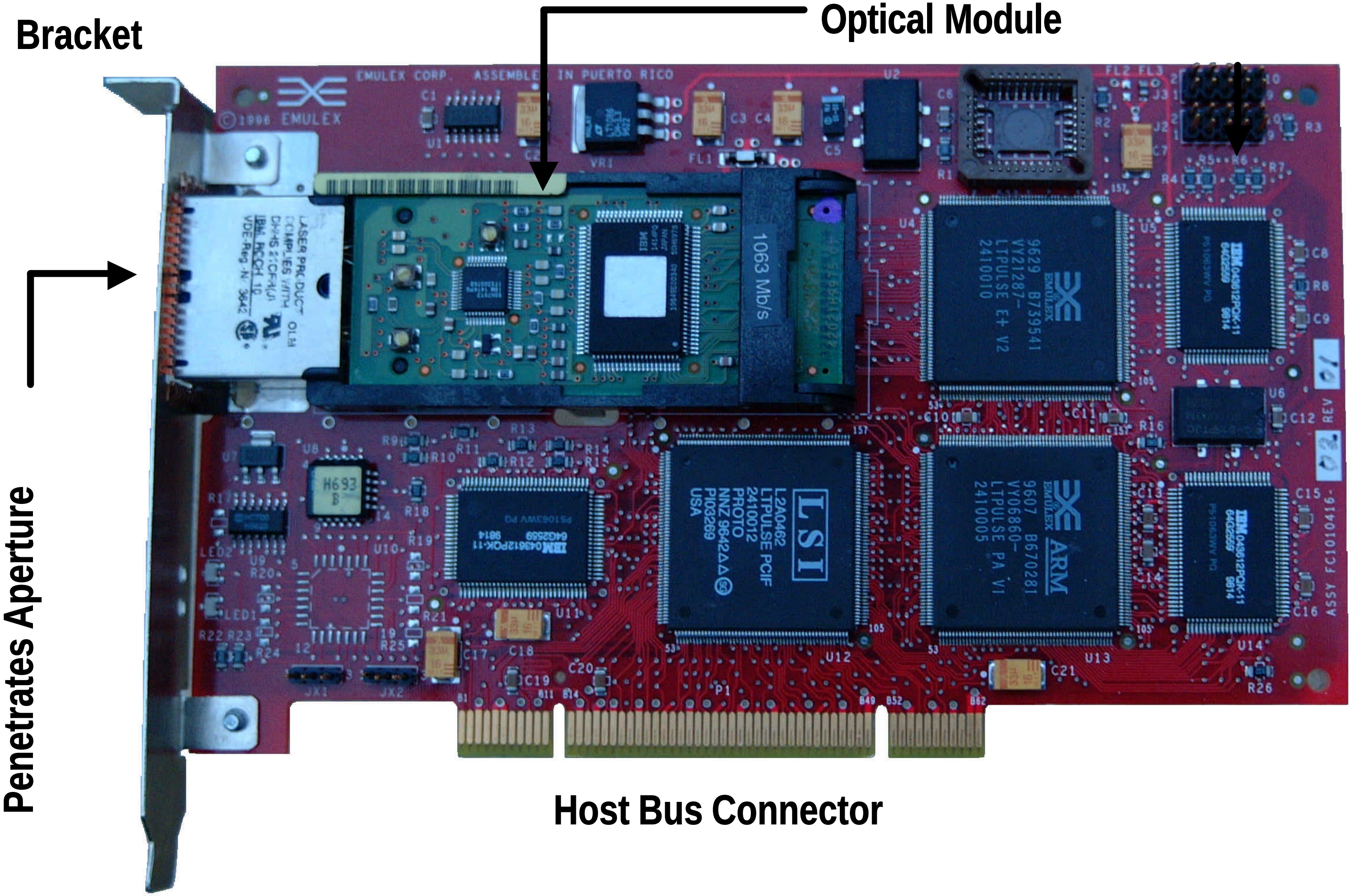
Optical Module

Host Bus Connector (on reverse side)

48-pin Connector (on reverse side of module)

Duplex-SC Fiber Receptacle

Photograph of HAC with optical module



Metal Bracket

Optical Module

Duplex-SC Fiber Receptacle Penetrates Aperture

Host Bus Connector

Review of Design Rules

And the shielding of apertures

Enclosure Design Rules

- EMC rules consider the 5th harmonic of the max frequency
- RF energy is inside enclosure, which must be “RF tight”
  - Usually metal enclosure acts as shield
  - Conductive polymers or plastic with conductive coating
  - Minimum requirements on shield thickness and conductivity
- Carefully control seams, louvers, backpanels, and other sources of RF emission “leakage” from enclosure
  - Rigorous and robust mechanical design
  - RF gaskets to maintain shield integrity
- Particular attention is paid to connector feedthroughs and apertures for ventilation, indicator lights, and displays
  - Limit number of apertures in shield
  - Limit maximum size of apertures in shield

Apertures in an Ideal Enclosure

- For RF of wavelength Λ, in general apertures smaller than a *half-wavelength* will not radiate RF
- The aperture is said to be “cut off” for $\Lambda > \Lambda_c$ i.e. for RF frequencies below a critical value called f_c
- For $f < f_c$, only evanescent (bound) solutions to Maxwells’ equations exist. Evanescent field amplitude decays exponentially within a few mm
- Assumes air; neglects waveguide and other effects

RF Cutoff Frequency Calculation for an Ideal Enclosure with an Aperture of size D

- The cutoff wavelength Λ_c may be found by setting

$$D = \Lambda_c / 2$$

$$\Rightarrow \quad \Lambda_c = 2D$$

- substituting

$$\Lambda \equiv c / f \qquad \text{where } c \cong 3 \times 10^8 \text{ m/sec}$$

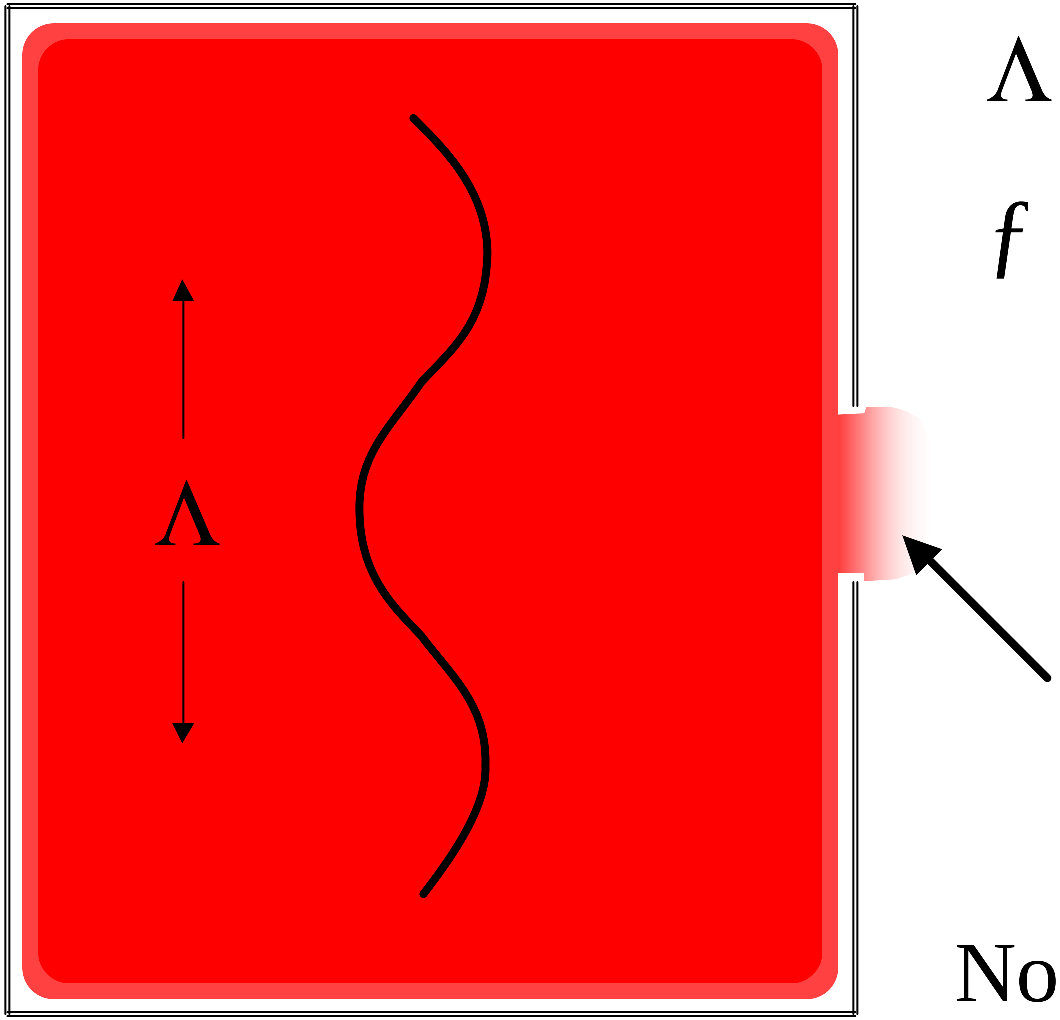
- yields the cutoff frequency f_c of an air-filled aperture

$$f_c = c / \Lambda_c = c / 2D$$

- Example: duplex-SC fiber aperture (D = 28 mm)

$$f_c \approx 5.4 \text{ GHz}$$

Low Frequency Inside Ideal Enclosure



$$\Lambda > 2D$$

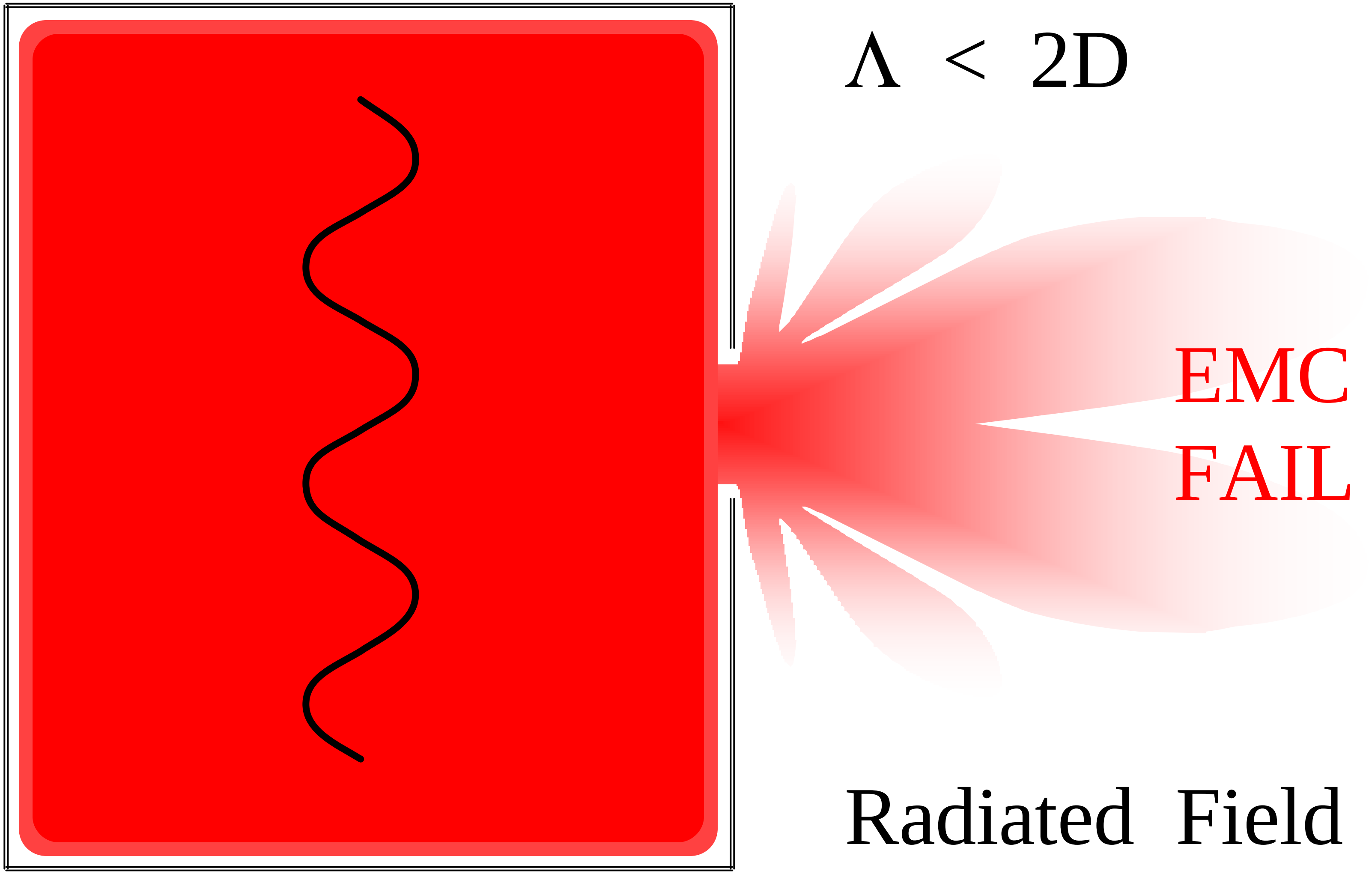
$$f < f_c$$

EMC
PASS

Evanescent
(bound) Field

No Radiated Field

High Frequency Inside Ideal Enclosure



$\Lambda < 2D$

EMC
FAIL

Radiated Field

Cutoff Frequency for Various Apertures

Fiber Connector	**Aperture Size D**	**Calculated f_c**
Duplex-SC	28 mm	5.4 GHz
Simplex-SC *	14 mm	10.7 GHz
MT-RJ	11 mm	14 GHz
2x SC Ferrule	5.0 mm	30 GHz
2x LC Ferrule	2.5 mm	60 GHz

* Or duplex-SC with conductive septum

Early Assumptions/Conventional Wisdom

- Optical fiber is a dielectric waveguide
  - Unperturbed fiber has no radiating optical modes, once EMD achieved
  - No RF emissions, even if light is modulated at high frequency
- Optical fiber cable is a dielectric
  - Fiber itself is made of glass
  - Cables used aramid fiber and polymer construction
  - Electrical isolation between equipment means no ground loops
  - Non-metallic cables exempt from conducted immunity EMC testing
- Several advantages over other communication technologies
  - Zero RF emissions
  - Easier to pass EMC regulatory hurdles
  - Immune to RF interference and ESD
  - Very secure and tap-resistant

Example: Gigabit Ethernet

- IEEE 802.3 Gigabit Ethernet 1.25 Gigabits/sec serial
- Maximum frequency (neglecting other sources) arises from a 101010… data pattern

$$f \quad = \quad 1250 \text{ Mbps} / 2 \quad = \quad 625 \text{ MHz}$$

- FCC requires testing of 5th harmonic of this signal

$$f \quad = \quad 5 \times 626 \text{ MHz} \quad = \quad 3.125 \text{ GHz}$$

- Air-filled duplex-SC aperture (D = 28 mm diagonal)
  - Cutoff frequency $f_c \approx 5.4$ GHz
  - Aperture is sufficiently small to contain 3.125 GHz
  - Margin: aperture will contain 8th harmonic (5 GHz)

Early Regulatory Failures

In normally RF-tight enclosures

Early Regulatory Failures

- Early adopters of optical fiber technology often used HAC “daughtercards” to upgrade existing system chassis
- These systems chassis were production items that had already undertaken EMC testing, and had passed with wide margin
- In the early 1990s, when fiber optic networking HACs were installed, formerly RF-tight products failed radiated emission in the 3 GHz range
- Equipment could not ship, causing consternation and delay
- Initially, individual vendors developed ad-hoc methods (usually involving more shielding) to pass EMC
- Eventually, multi-source agreements (MSAs) standardized
- WHY WERE THERE EMC FAILURES ??

Open Air Test Site (OATS) for Testing

Control room not shown

Calibrated Antenna →

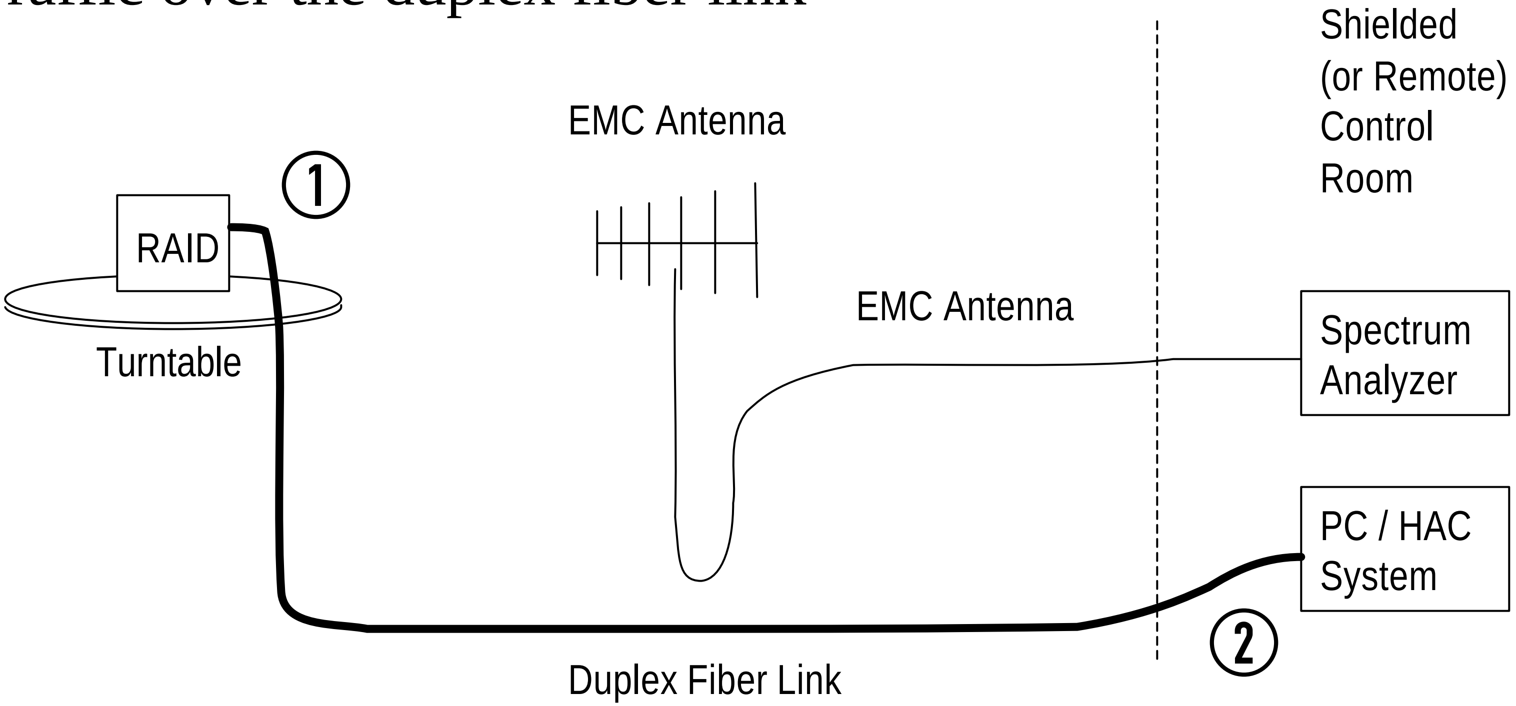
Ground →

← Turntable is Inside Wooden Structure

Courtesy UL

EMC Test Setup for Radiated Emission

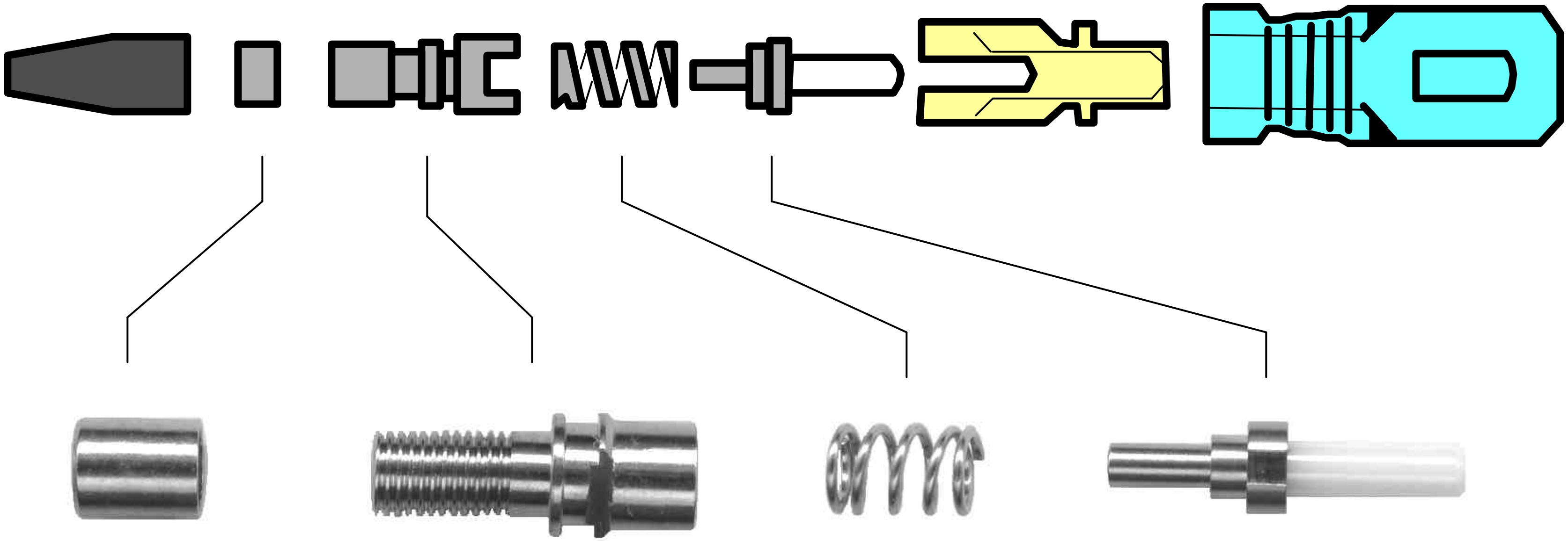
- “Engineering scans” done, not formal EMC testing
- Follow EMC test protocols
- Carefully calibrated test equipment
- Traffic over the duplex fiber link



Observations and Serendipity

- Fiber connected at ① (on turntable) and ② (outside OATS)
  - Observed high RF emissions
- Unplugged connector ①, observed low RF emissions
  - No traffic. Observed low (baseline) RF emissions
- Reinstalled connector ①, traffic reestablished
- Unplugged connector ② (outside OATS)
  - No traffic. Observed high RF emissions
  - RF emissions should be the <u>same</u> for unplugging either connector
- Accidental observation of emission while connector ① was unplugged from the RAID system duplex-SC receptacle
  - Observed high RF emissions when <u>metal</u> screwdriver near aperture
  - RF emissions dropped to baseline when screwdriver was withdrawn
- Deconstructed several optical fiber connectors

Exploded View of SC Connector



Rubber
Boot

Plastic
Housing

Plastic
Body

Crimp
Ring

Stop
Ring

Ferrule
Spring

Ferrule with
Ceramic Tip

TYPICAL CONDUCTIVE PARTS

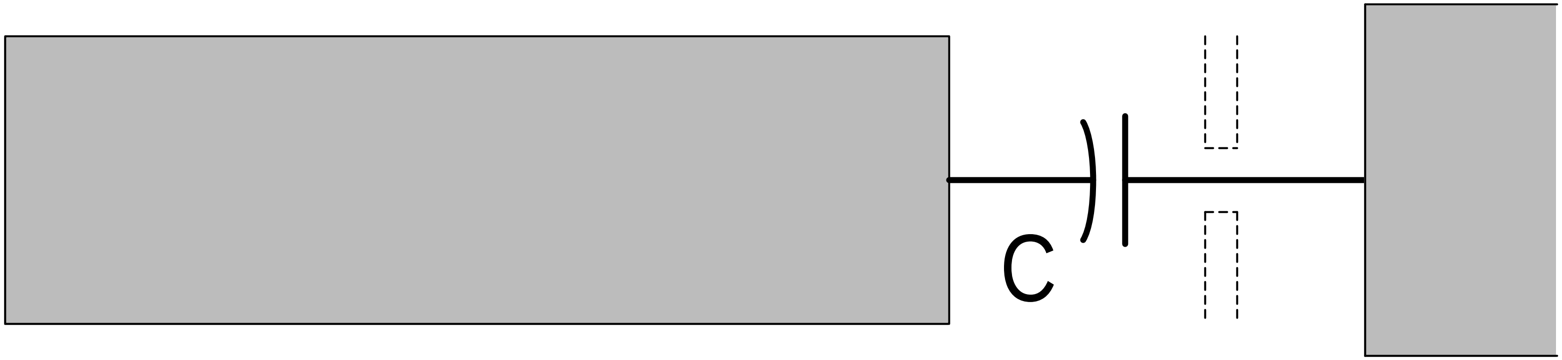
Proposed Model

Small conductive parts in fiber-optic connectors cause RF emission failures

Proposed Equivalent Circuit for Model

- Shield and aperture shown by phantom lines

= Metallic body with parasitic capacitance C to inside shield



Magnitude of Capacitance

- At high frequencies a 1 pF capacitance is low impedance

$$Z \quad = \quad \frac{1}{2\,\pi\, f\, C} \angle\text{-}90^\circ \quad \approx \quad -\ 16\, j \quad \text{ohms} \quad \text{at 10 GHz}$$

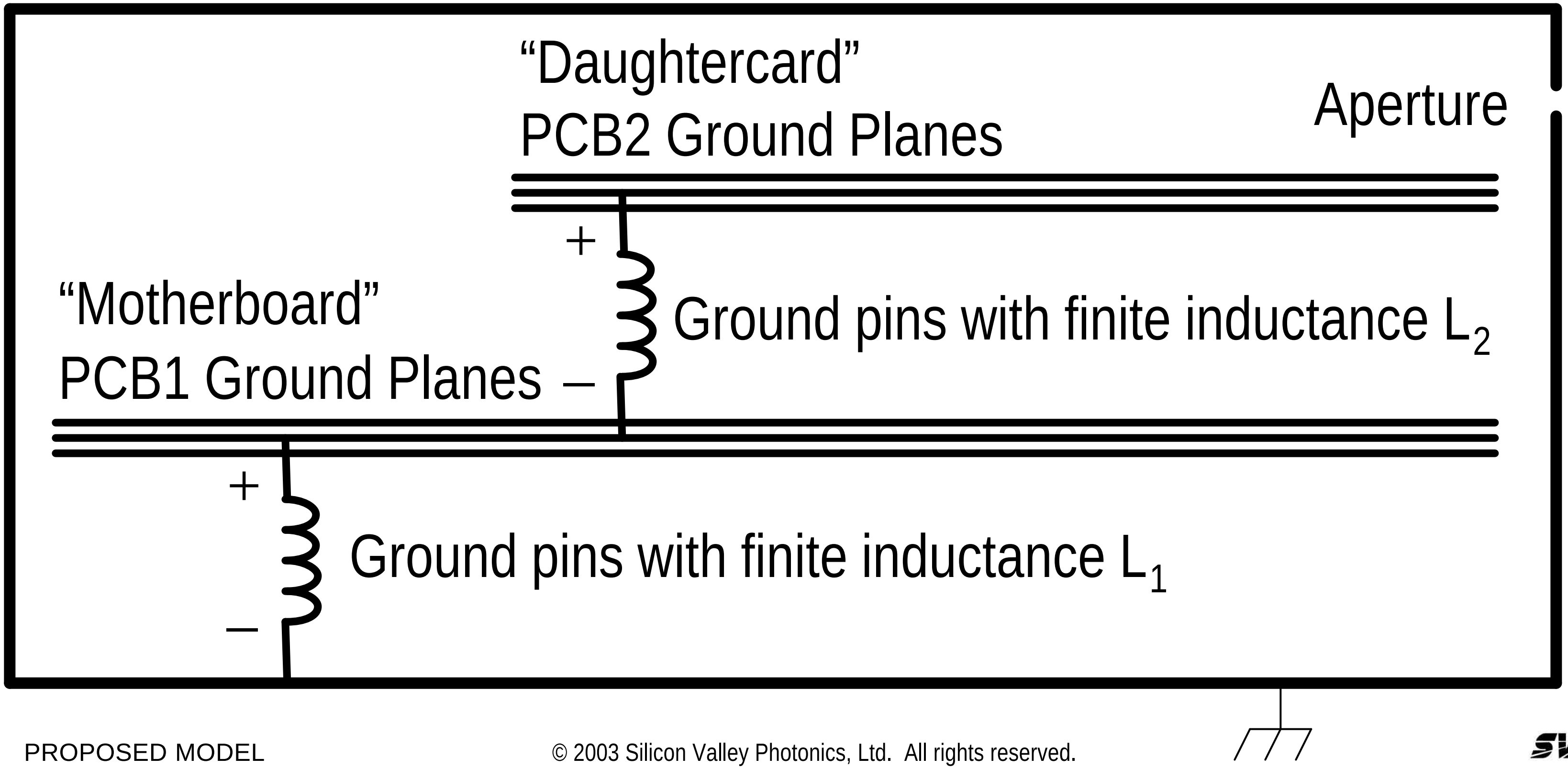
- Optical connectors that have finite capacitance to within the enclosure may be easily driven by potential differences V

$$I \ = \ V / Z$$

- For example, a 28 mm × 12 mm parallel plate capacitor separated by 1mm air gap results in 3 pF capacitance
- Assume there will be some finite capacitance to within chassis
- There will also be capacitance to the chassis itself (ignore)

Where does driving voltage come from?

- Propose V potential across parasitic inductances
- PCB-to-PCB connectors, e.g. optical module on HAC
- Finite impedance between ground planes in PCB stack



Magnitude of Inductance

- All electrical connectors have parasitic inductance.
- At high frequencies, a 1 nH inductance presents impedance

$$Z \quad = \quad 2\,\pi\, f\, L\ \angle 90^\circ \quad \approx \quad +\,63\ j \quad \text{ohms} \quad \text{at 10 GHz}$$

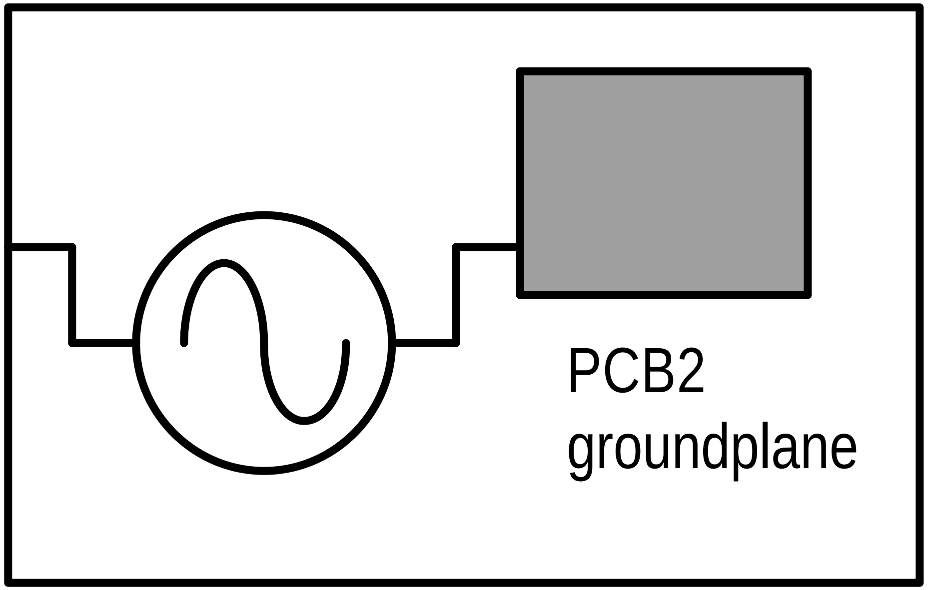
- Connector parasitic inductance needs to be minimized in high-speed PCB-to-PCB electrical interconnect
- Parasitic inductance will generate a voltage difference proportional to the current passing through the connector

$$V = Z\ I$$

- For example, groundplane-to-groundplane
  - Ground is no longer homogeneous
  - Transient voltage differences between ground planes in PCB stack
  - Well-understood, and commonly called “ground bounce”

Ideal Enclosure with RF Voltage Source

- Replace voltage across parasitic inductance with a Thévenin-equivalent voltage source of the correct amplitude, impedance, phase, frequency, etc.
- Assume motherboard is well-grounded to chassis

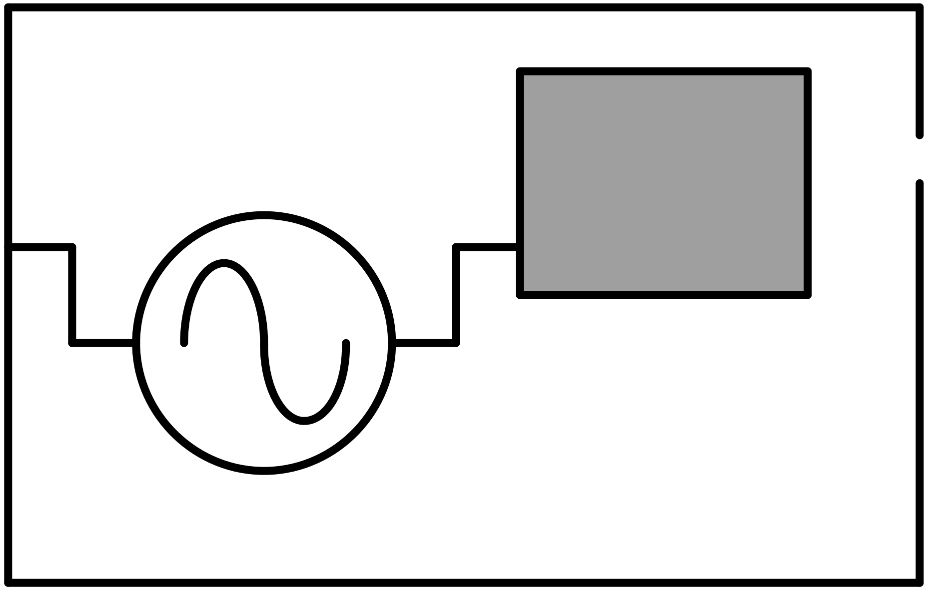


100%
Shielded

No Dipole
=
No Fields

Enclosure with Aperture in Cutoff Regime

- For $f < f_c$, there is no radiated emission
- For $f < f_c$, there is only evanescent (bound) field within a few millimeters of the aperture
- There is no radiated solution to Maxwell’s equations

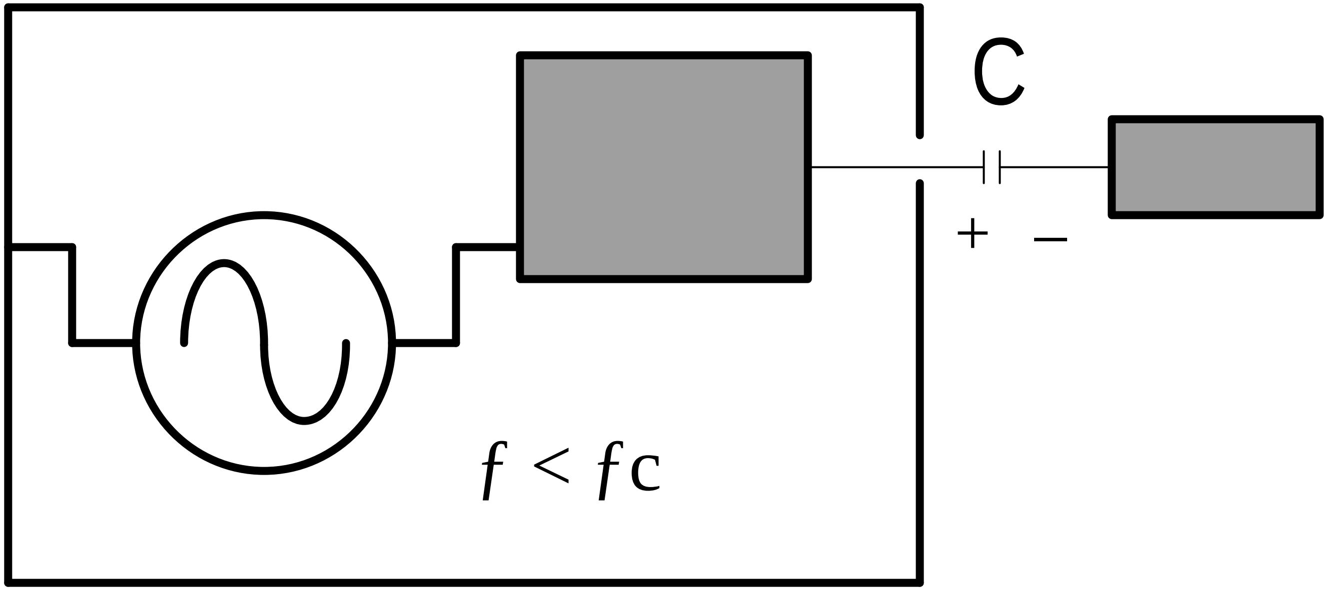


Evanescent Field Only

No Radiated RF Emission

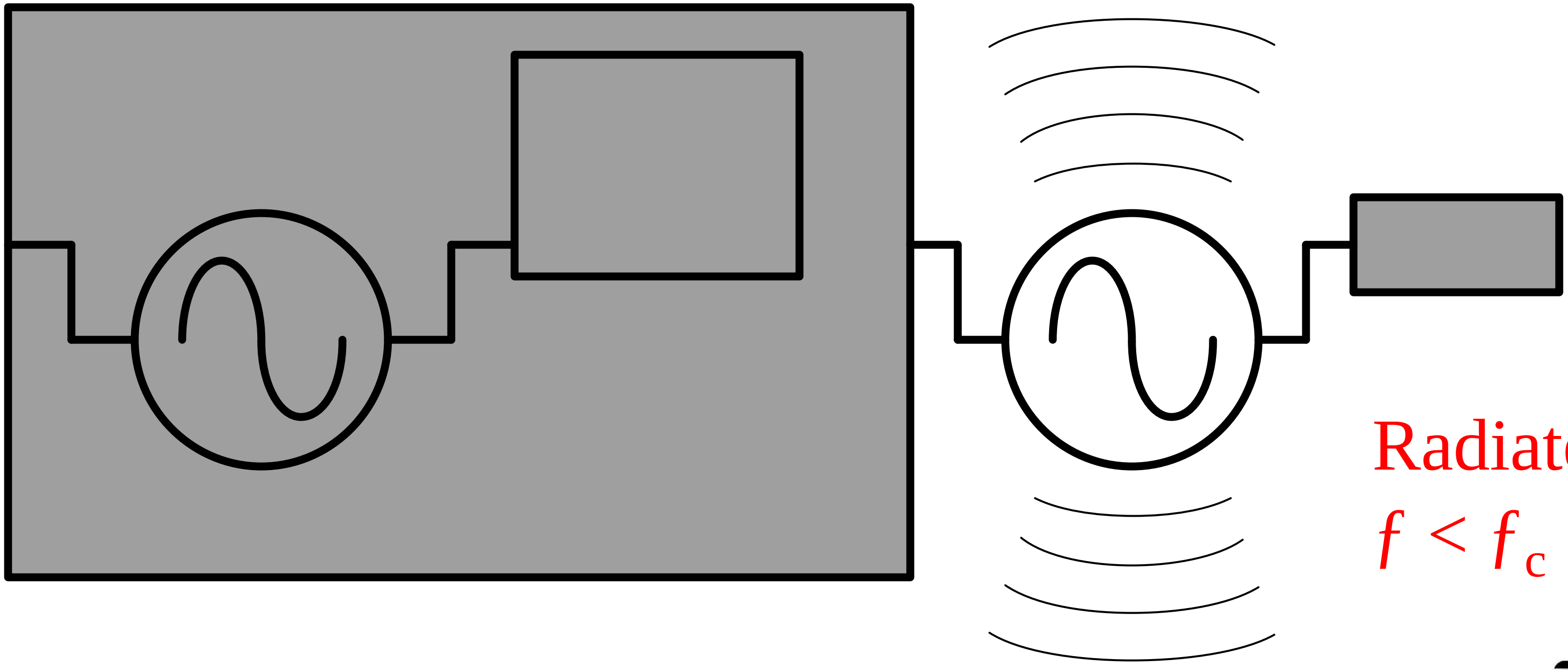
Enclosure with Metallic Body Near Aperture

- Assume a finite parasitic capacitance C exists via the aperture, between the interior ground plane to the exterior metallic body
- High-frequency currents through C induces potential



Resultant Equivalent Circuit

- Replace voltage across parasitic capacitance with Thévenin-equivalent voltage source as before
- The proposed model is that a new dipole is created between the chassis and the external metallic body



Radiates

$f < f_c$

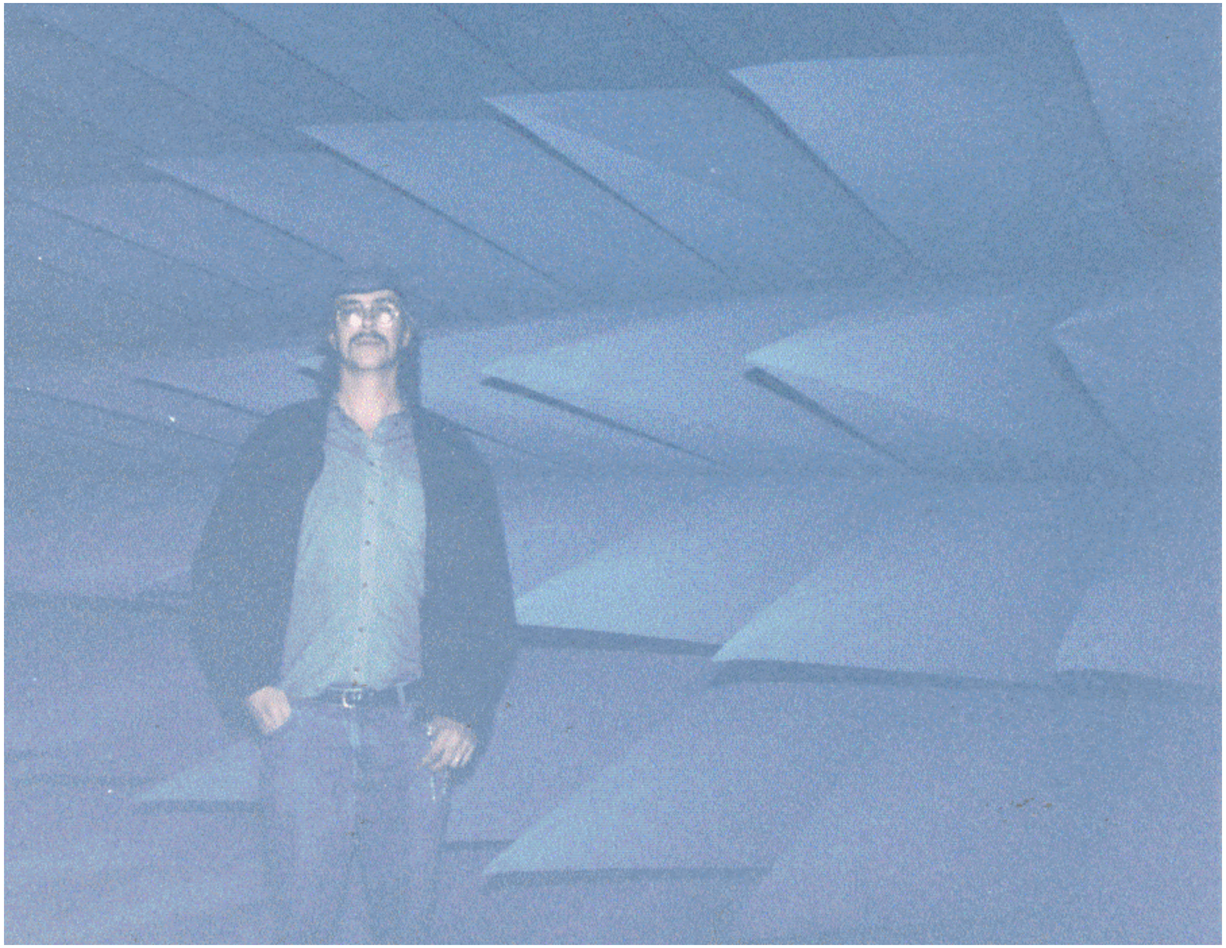
Experiments

Three tests to validate hypothesis

Experimental Overview

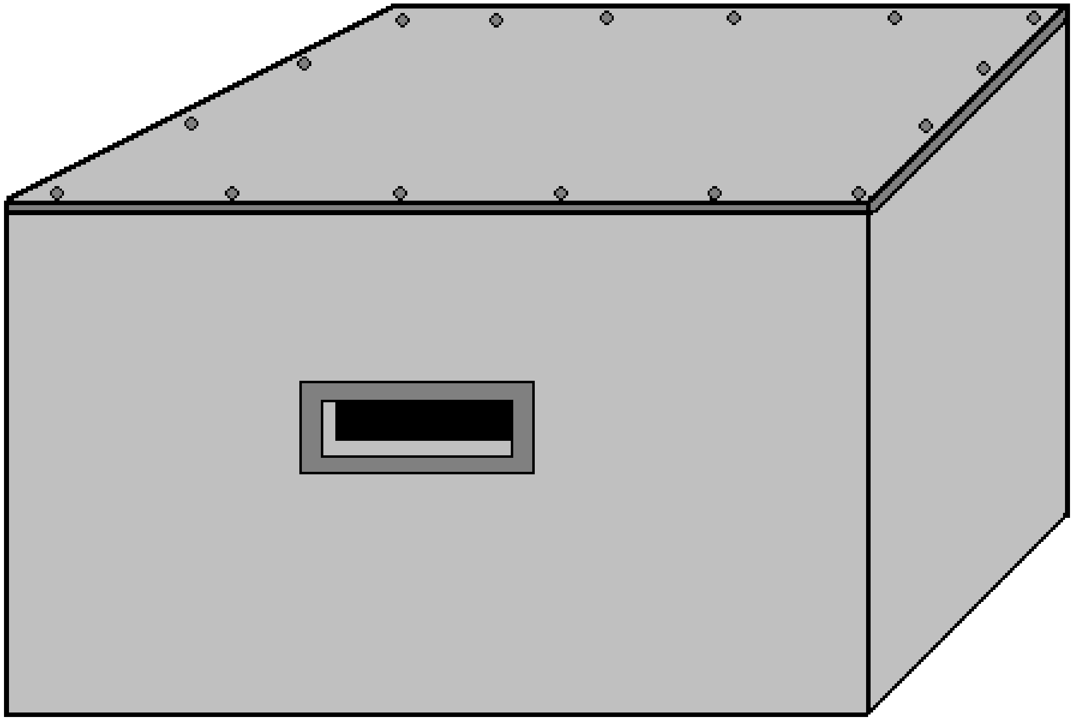
- Demonstrate that the proposed model qualitatively explains failure mechanism
- Constructed a battery-powered enclosure with ground plane stack and internal RF source
- Measure electromagnetic emissions at EMC test site
  - Maximum emissions, with respect to angle and elevation
  - Emission measurement accuracy ± 4 dB
- Introduce external metallic body near aperture
- Verify RF emission for $f < f_c$ condition
- Verify ultimate source of driving voltage

Inside 10 meter Semi-Anechoic Chamber

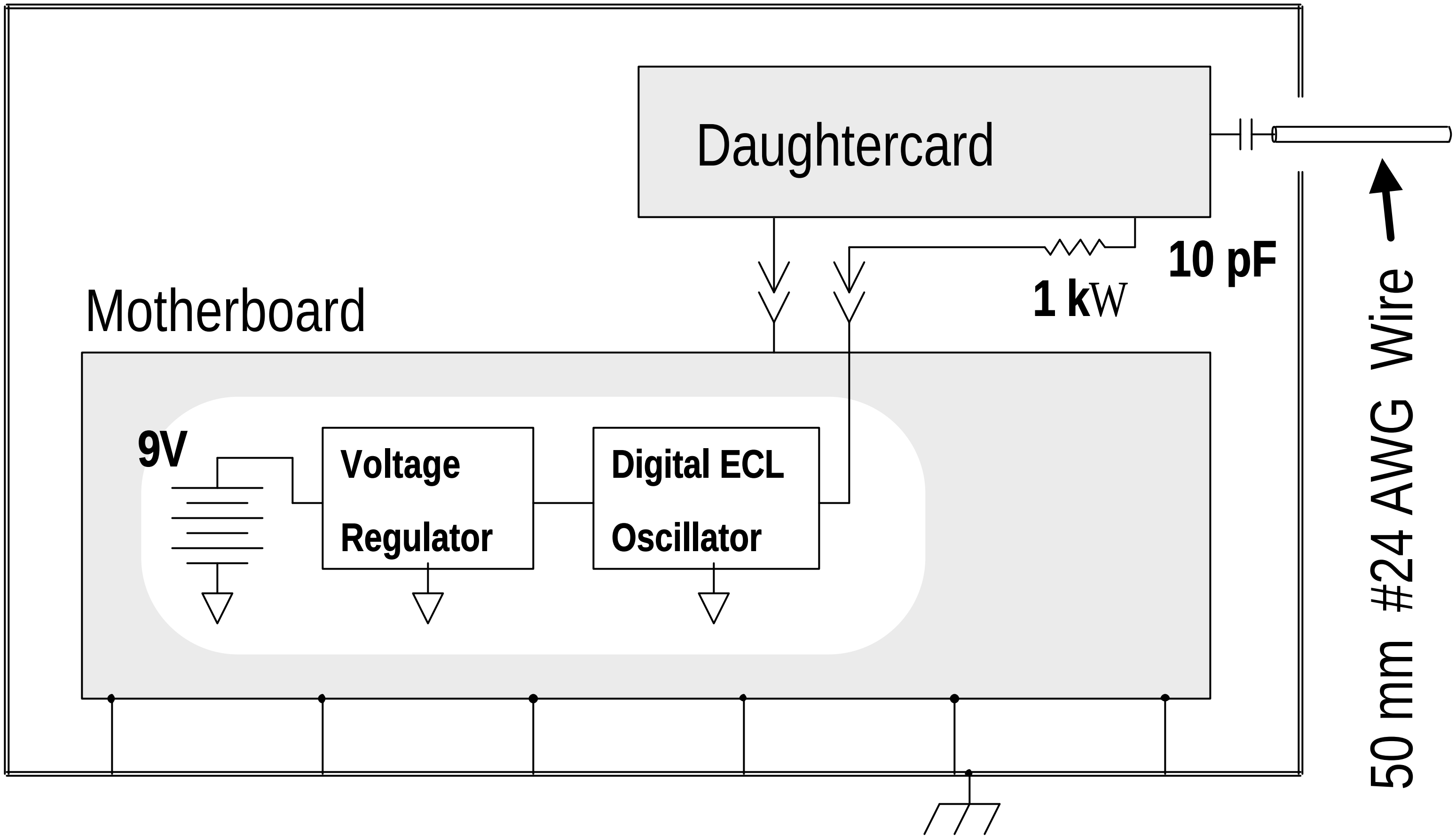


Experimental Test Enclosure

- Attempt to simulate computer system with aperture
- 20 cm × 30 cm × 28 cm Bud™ box
- RF gasket and many screws to seal the cover



Schematic of RF-Generating Circuit



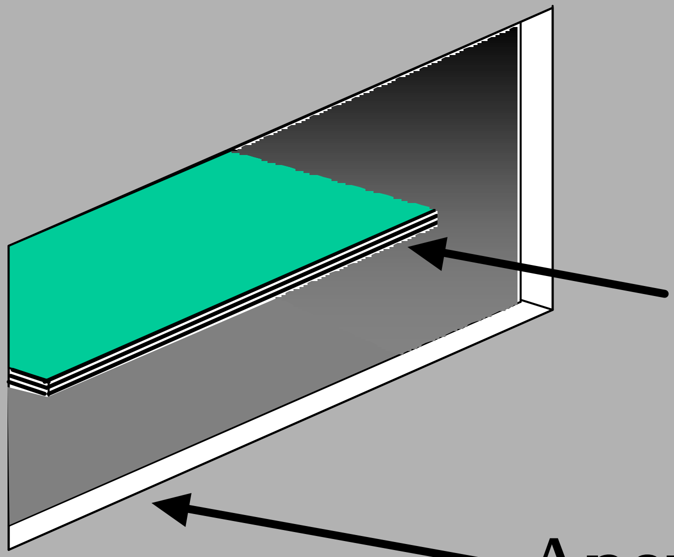
Experimental Details

- RF-tight enclosure with 28 mm × 12 mm aperture
- Motherboard ground plane has multiple low-impedance connections to the chassis, neglect L_1
- Battery-powered RF energy source on motherboard
  - Ecliptec 160 MHz ECL oscillator
  - 1.1 nsec rise/fall times (f components slightly below 1 GHz)
- Daughtercard connected via 48-pin PCB-to-PCB connector
  - 1 signal pin and 1 ground pin
- 1 kΩ mismatched load (to maximize RF) on daughtercard
- External metallic body simulated by 50 mm of #24 AWG wire
- 10 pF coupling capacitor between external metallic body and daughtercard ground plane

Experiment #1

Confirmation of dipole model

Experiment 1A - Aperture Only

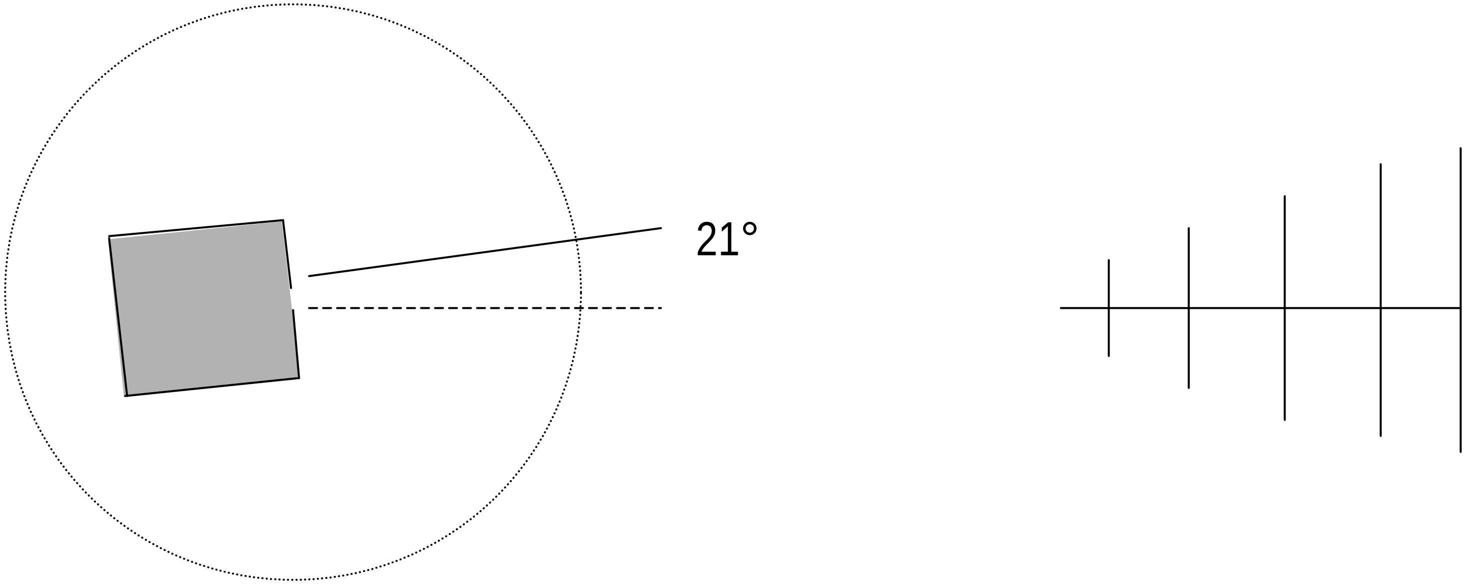


Edge of Daughtercard
28 mm from Aperture

Aperture in Front Panel
28 mm × 12 mm

NOT TO SCALE

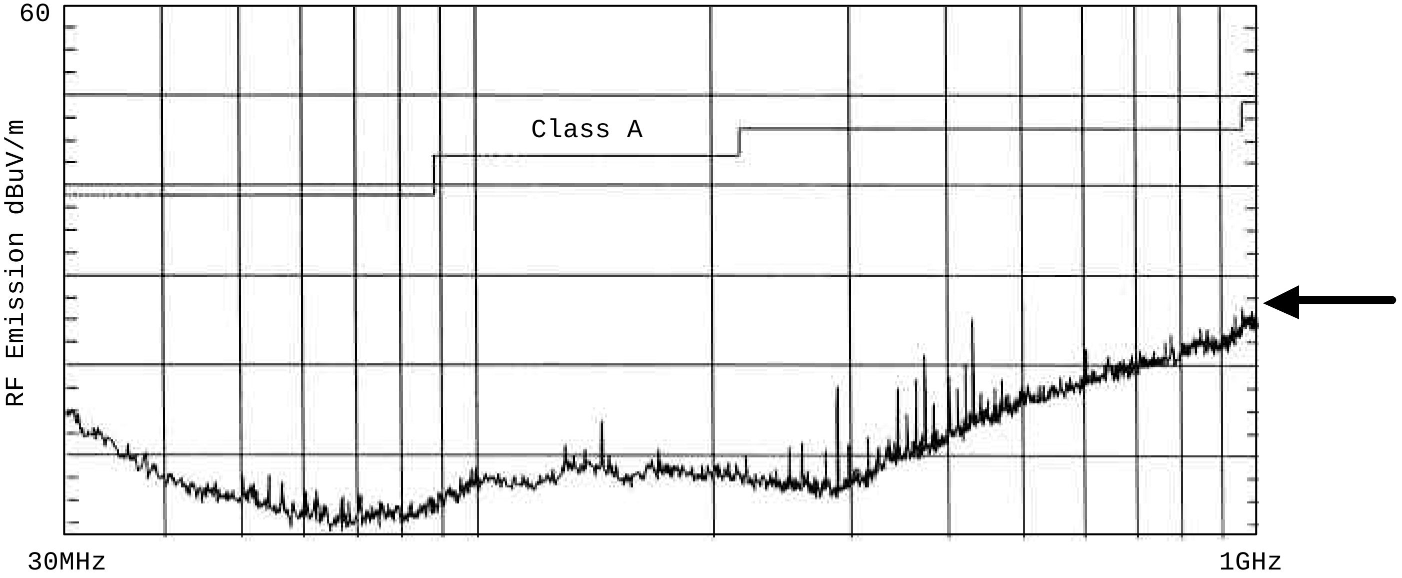
1A - RF Emissions from Aperture Only



- Place test box on turntable and rotate for maximum emissions
  - Angle = 21° Vertical offset = 0
- Demonstrates enclosure is RF-tight, aperture is in cutoff regime
  - Very Low far-field RF emissions from open aperture
  - RF Emission = 26.4 dBuV/m at 957.5 MHz
    (20 dB margin below FCC Class A)
- Evanescent RF could be detected with near-field probe

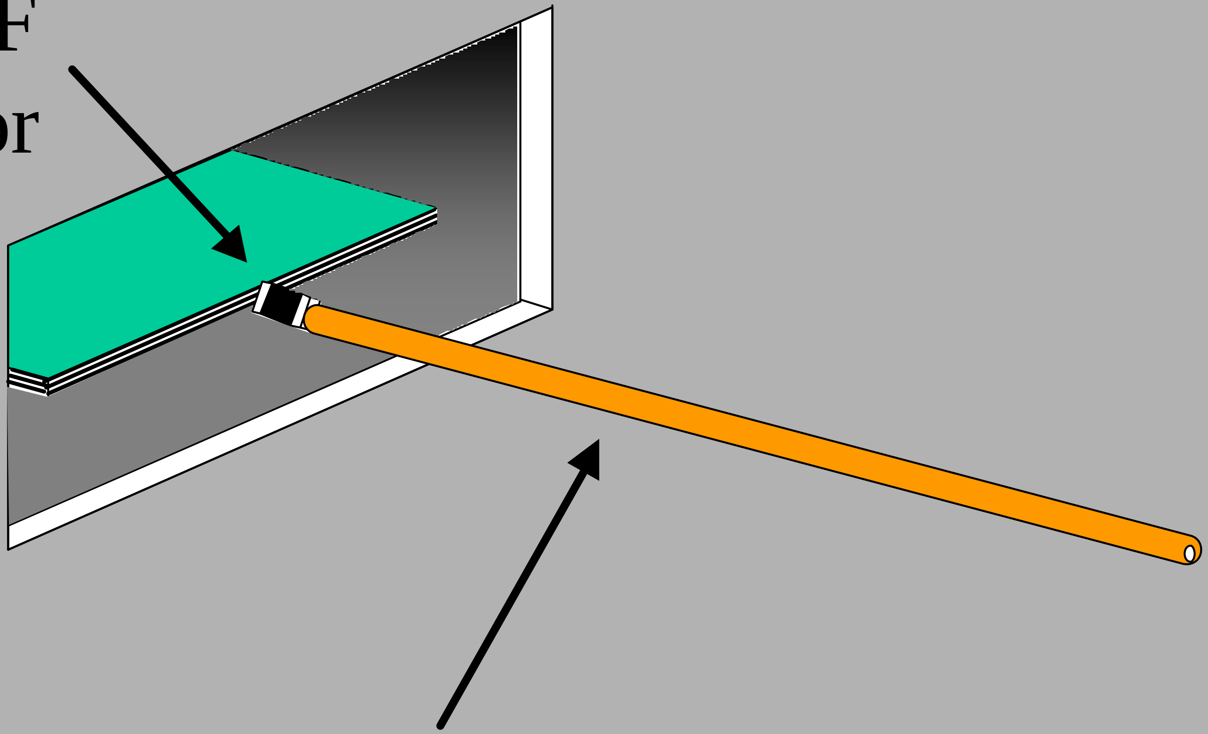
1A - RF Emission as a Function of *f*

- Baseline Measurement – No External Metallic Body
- Aperture in cutoff mode for < 1 GHz, low emissions



Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCF	Probe CF	Coax CF	Preamp CF
957.5	26.36	46.4	-20	21	102	0	6.92	25.2	6.4	24.7
936.25	25.55	46.4	-20.8	21	102	0	5.79	24.1	6.08	24.4
431	25.16	46.4	-21.2	21	102	1	-4.84	15.8	3.84	24.5
846.25	24.26	46.4	-22.1	21	102	1	5.46	23.8	6.08	24.4
907.5	23.57	46.4	-22.8	21	102	0	4.77	23.4	5.76	24.4
775	23.38	46.4	-23	21	102	0	3.3	22.3	5.44	24.4
831.25	23.31	46.4	-23.1	21	102	1	4.83	23.8	5.76	24.7
997.5	25.67	49.5	-23.8	21	102	0	7.19	25.2	6.4	24.4
30.525	15.14	39	-23.9	21	102	1	-5.26	18.9	0.96	25.1
602.5	21.75	46.4	-24.7	21	102	1	0.706	20	5.12	24.4
707.5	21.71	46.4	-24.7	21	102	1	1.95	21.5	5.12	24.7
737.5	21.7	46.4	-24.7	21	102	0	2.9	21.9	5.44	24.4
373.5	21.12	46.4	-25.3	21	102	1	-7.6	13.4	3.52	24.5
643.75	21.1	46.4	-25.3	21	102	1	1.98	21.3	5.12	24.4

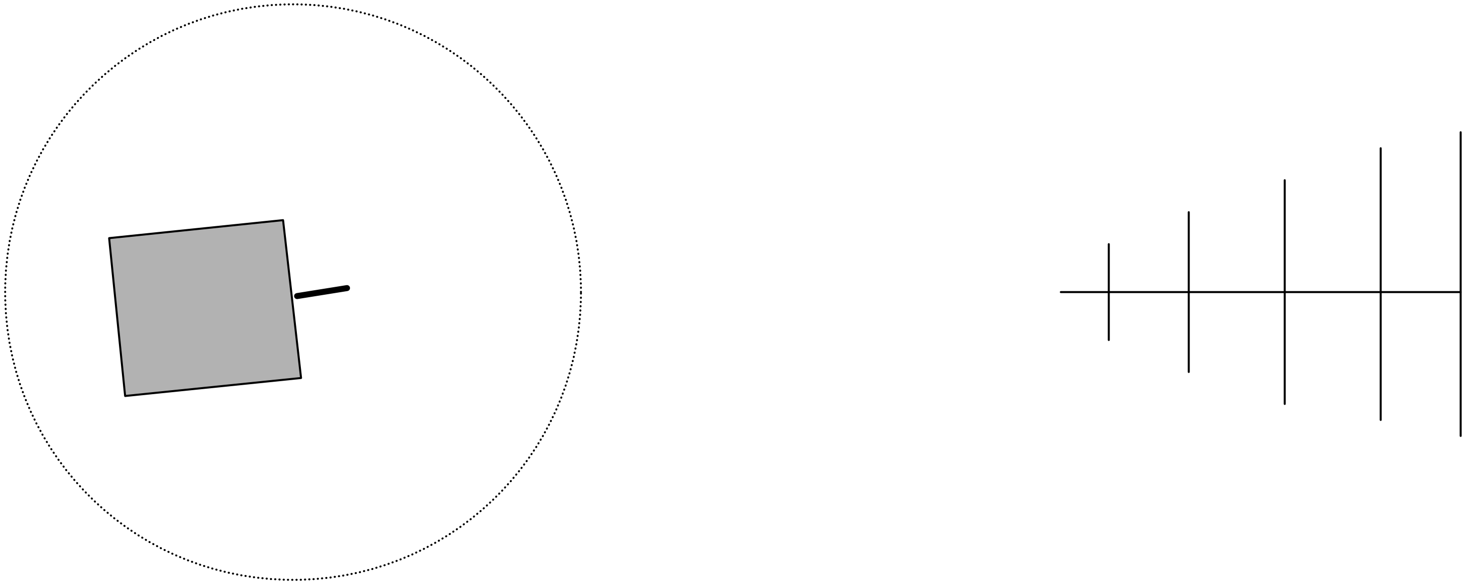
Experiment 1B – Wire and Capacitor



10 pF
Capacitor

50 mm of #24 AWG Copper Wire

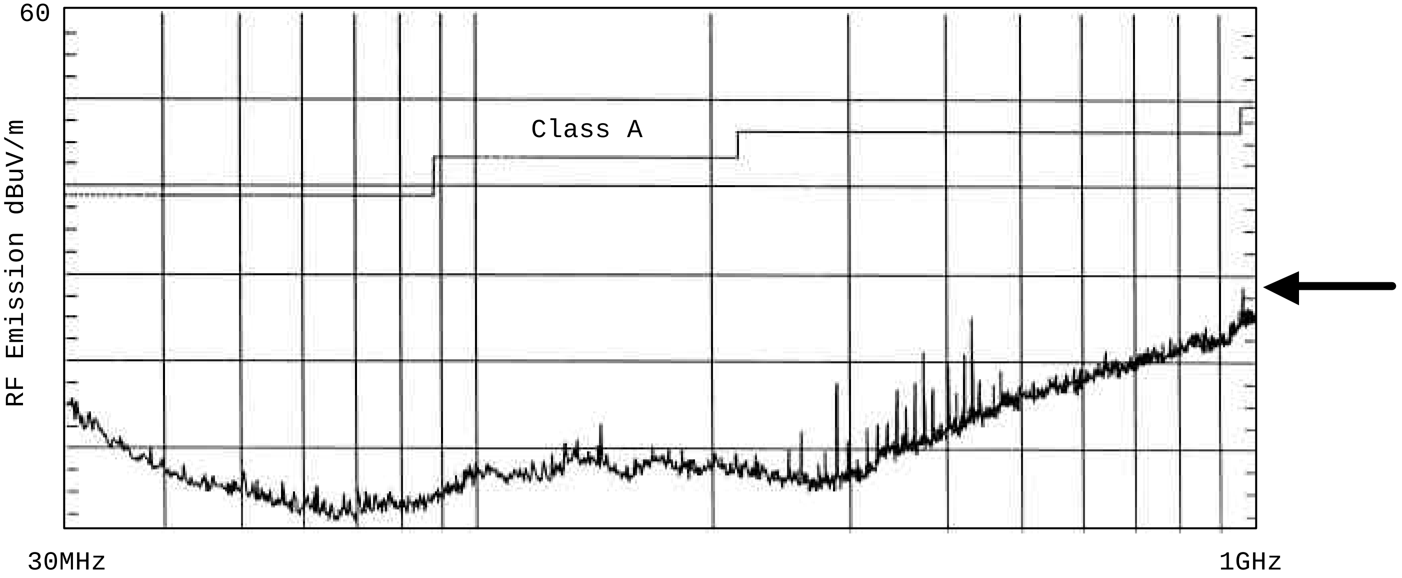
1B - Ext Metallic Body with Coupling Cap

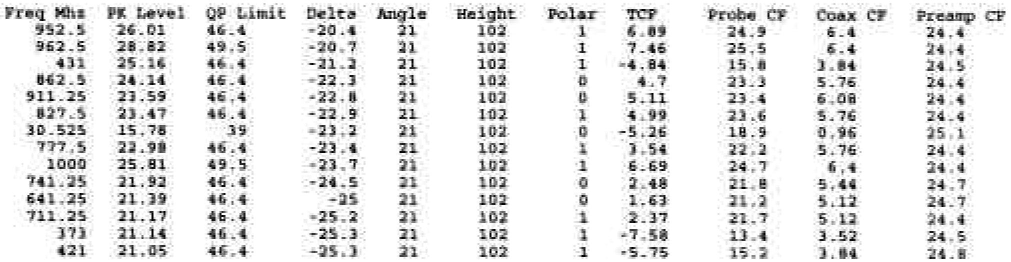


- Added 50mm long #24 AWG wire and 10 pF coupling cap
- Carefully reposition box on turntable, do not change angle
  - Angle = 21° Vertical offset = 0
- Slight, in RF emissions above experimental noise floor
  - RF Emission = 26. 0 dBuV/m at 952.5 MHz
    (20.4 dB margin below FCC Class A)

1B - RF Emission as a Function of *f*

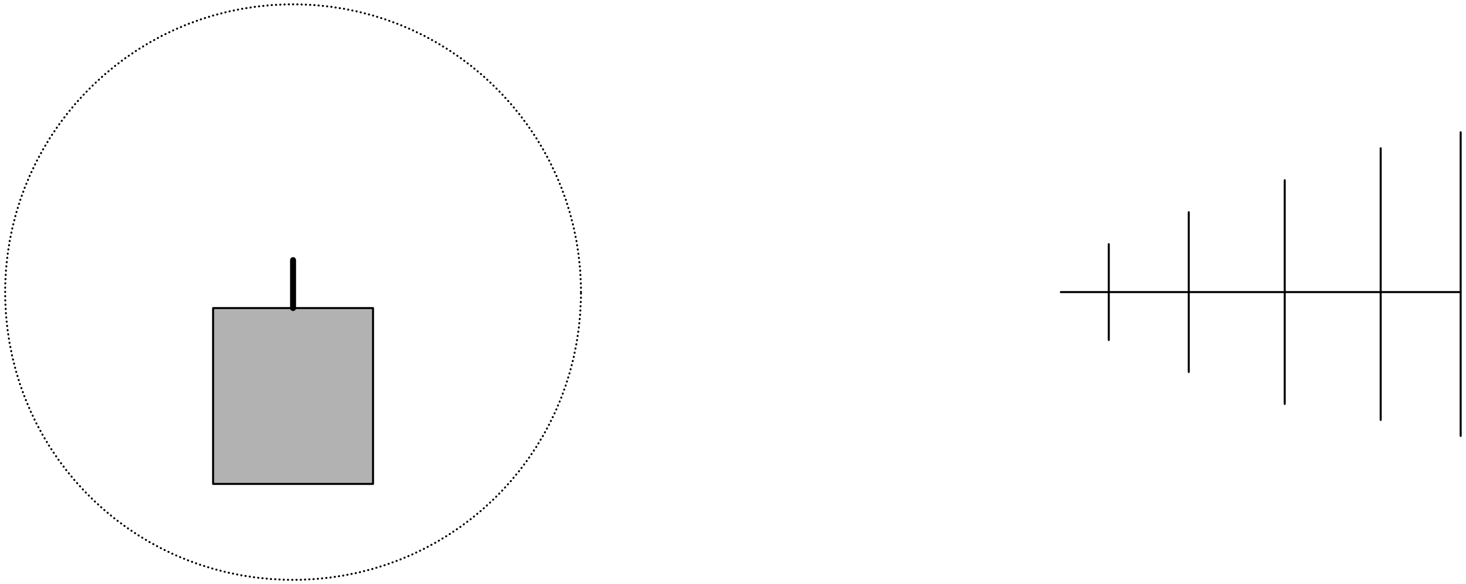
- Ext Metallic body and 10 pF capacitor present
- Some RF emission noted at 961 MHz





Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCF	Probe CF	Coax CF	Preamp CF
952.5	26.01	46.4	-20.4	21	102	1	6.89	24.9	6.4	24.4
962.5	28.82	49.5	-20.7	21	102	1	7.46	25.5	6.4	24.4
431	25.16	46.4	-21.2	21	102	1	-4.84	15.8	3.84	24.5
862.5	24.14	46.4	-22.3	21	102	0	4.7	23.3	5.76	24.4
911.25	23.59	46.4	-22.8	21	102	0	5.11	23.4	6.08	24.4
827.5	23.47	46.4	-22.9	21	102	1	4.99	23.6	5.76	24.4
30.525	15.78	39	-23.2	21	102	0	-5.26	18.9	0.96	25.1
777.5	22.98	46.4	-23.4	21	102	1	3.54	22.2	5.76	24.4
1000	25.81	49.5	-23.7	21	102	1	6.69	24.7	6.4	24.4
741.25	21.92	46.4	-24.5	21	102	0	2.48	21.8	5.44	24.7
641.25	21.39	46.4	-25	21	102	0	1.63	21.2	5.12	24.7
711.25	21.17	46.4	-25.2	21	102	1	2.37	21.7	5.12	24.4
373	21.14	46.4	-25.3	21	102	1	-7.58	13.4	3.52	24.5
421	21.05	46.4	-25.3	21	102	1	-5.75	15.2	3.84	24.8

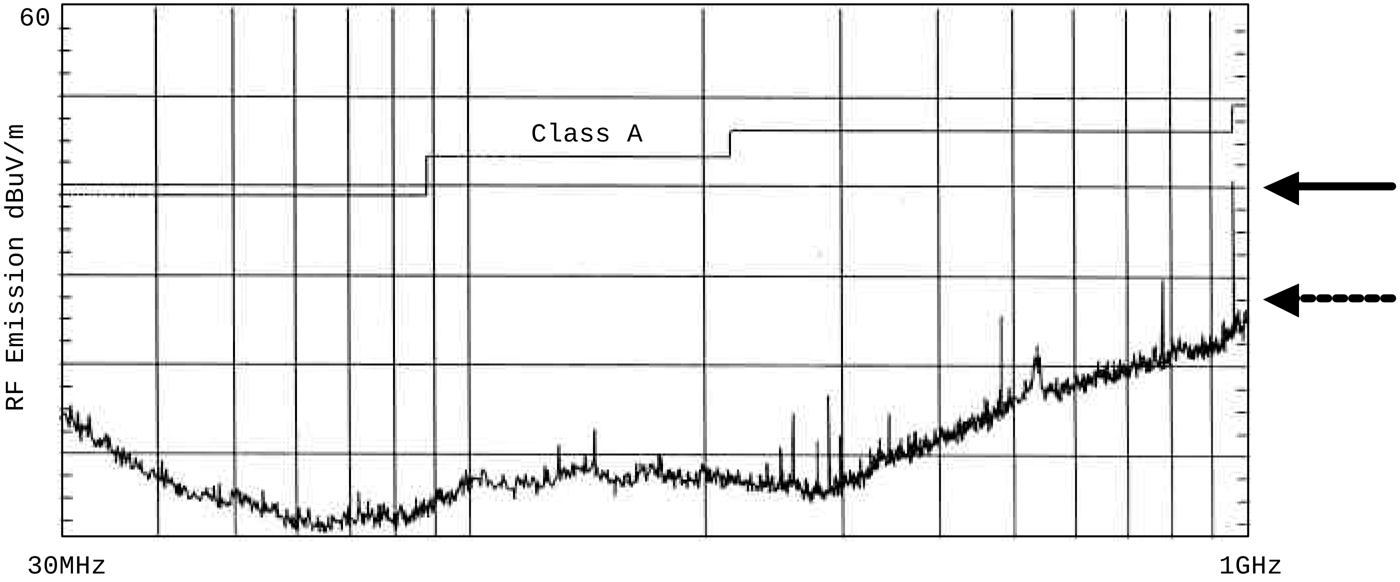
1C – Optimize Angle and Vertical Offset



- Rotate turntable to achieve maximum emissions
  - Angle = 89° Vertical offset = 0
- Classic dipole radiation pattern noted during rotation
- Large increase in RF Emissions
  - RF Emission = 41.0 dBuV/m at 961.25 MHz
    (8.5 dB margin below FCC Class A)

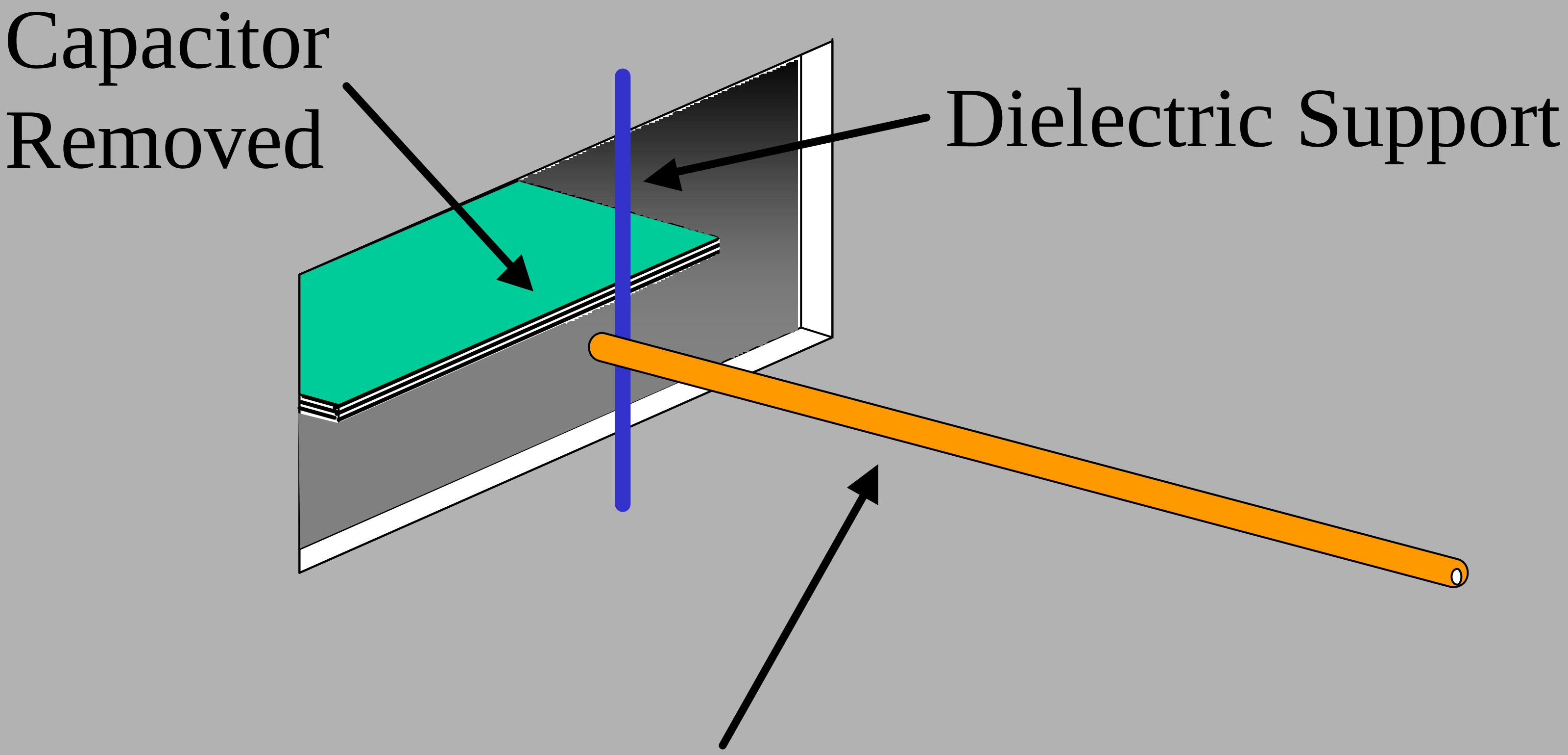
1C - RF Emission as a Function of *f*

- After rotating to find maximum emissions at 89°
- Large increase in 961 MHz and other emissions



Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCP	Probe CF	Coax CF	Preamp CF
961.25	40.99	49.5	-8.51	89	102	1	6.83	25.1	6.08	24.4
777.5	29.7	46.4	-16.7	89	102	1	3.54	22.2	5.76	24.4
481	25.59	46.4	-20.8	89	102	1	-2.81	17.5	4.16	24.5
932.5	25.32	46.4	-21.1	89	102	1	5.24	23.9	5.76	24.4
877.5	23.8	46.4	-22.6	89	102	1	5.32	23.3	6.08	24.1
818.75	23.34	46.4	-23.1	89	102	1	4.54	23.5	5.76	24.7
873.75	23.14	46.4	-23.3	89	102	1	4.66	23.3	6.08	24.7
30.875	15.53	39	-23.5	89	102	1	-5.51	18.7	0.96	25.1
998.75	25.58	49.5	-23.9	89	102	1	7.1	24.8	6.72	24.4
536.25	22.45	46.4	-24	89	102	1	-1.47	18.8	4.48	24.7
726.25	21.87	46.4	-24.5	89	102	1	2.75	21.7	5.44	24.4
713.75	21.5	46.4	-24.9	89	102	1	2.38	21.7	5.12	24.4
642.5	20.77	46.4	-25.6	89	102	1	1.97	21.2	5.12	24.4
633.75	19.69	46.4	-26.7	89	102	1	1.53	21.1	4.8	24.4

Experiment 1D – Wire Only

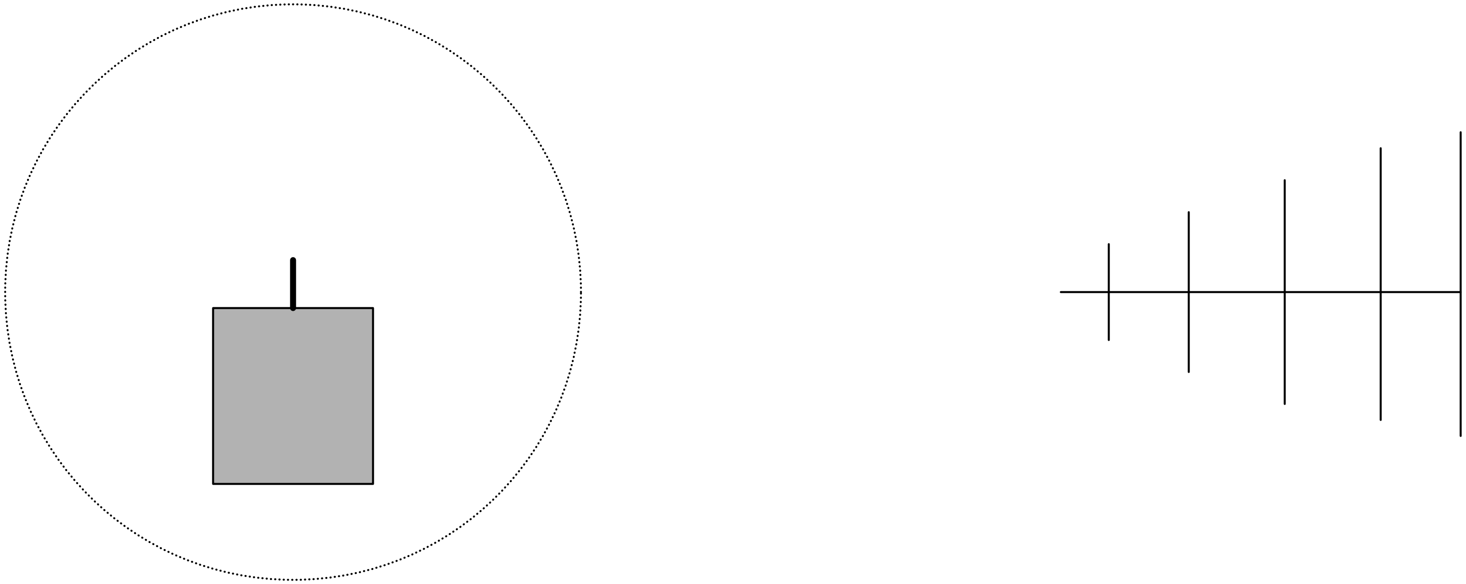


Capacitor Removed

Dielectric Support

50 mm of #24 AWG Copper Wire

1D - External Metallic Body Only



- Remove 10 pF capacitor and reposition wire in place
- Carefully return system to position of maximum emissions.
  - Angle = 89° Vertical offset = 0
- RF Emission observed to drop to slightly above baseline
  - RF Emission = 29.0 dBuV/m at 961.25 MHz

Experiment #1 Summary

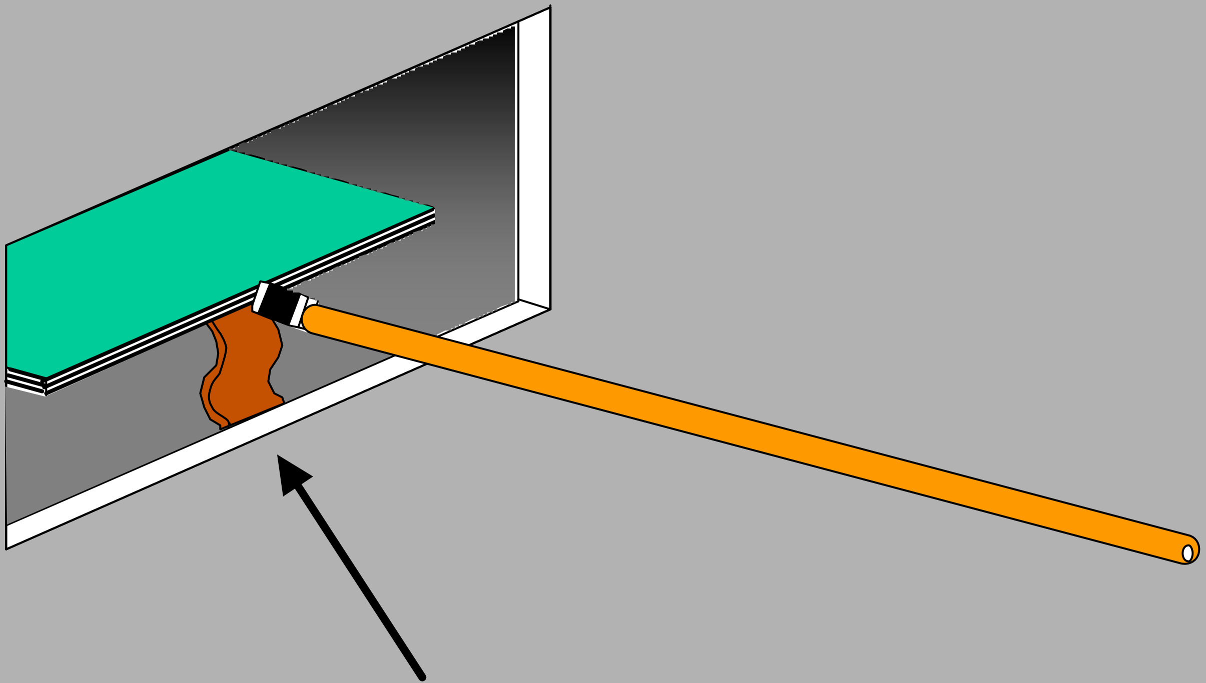
No.	Angle	Cap	Wire	MHz	dBuV/m
1A	22°	No	No	957	26.4
1B	22°	10 pF	Yes	952	26.0
1C	89°	10 pF	Yes	961	41.0
1D	89°	No	Yes	961	29.0

- Dipole model is confirmed, maximum near 90°
- Emission is strongly dependent on capacitance

Experiment #2

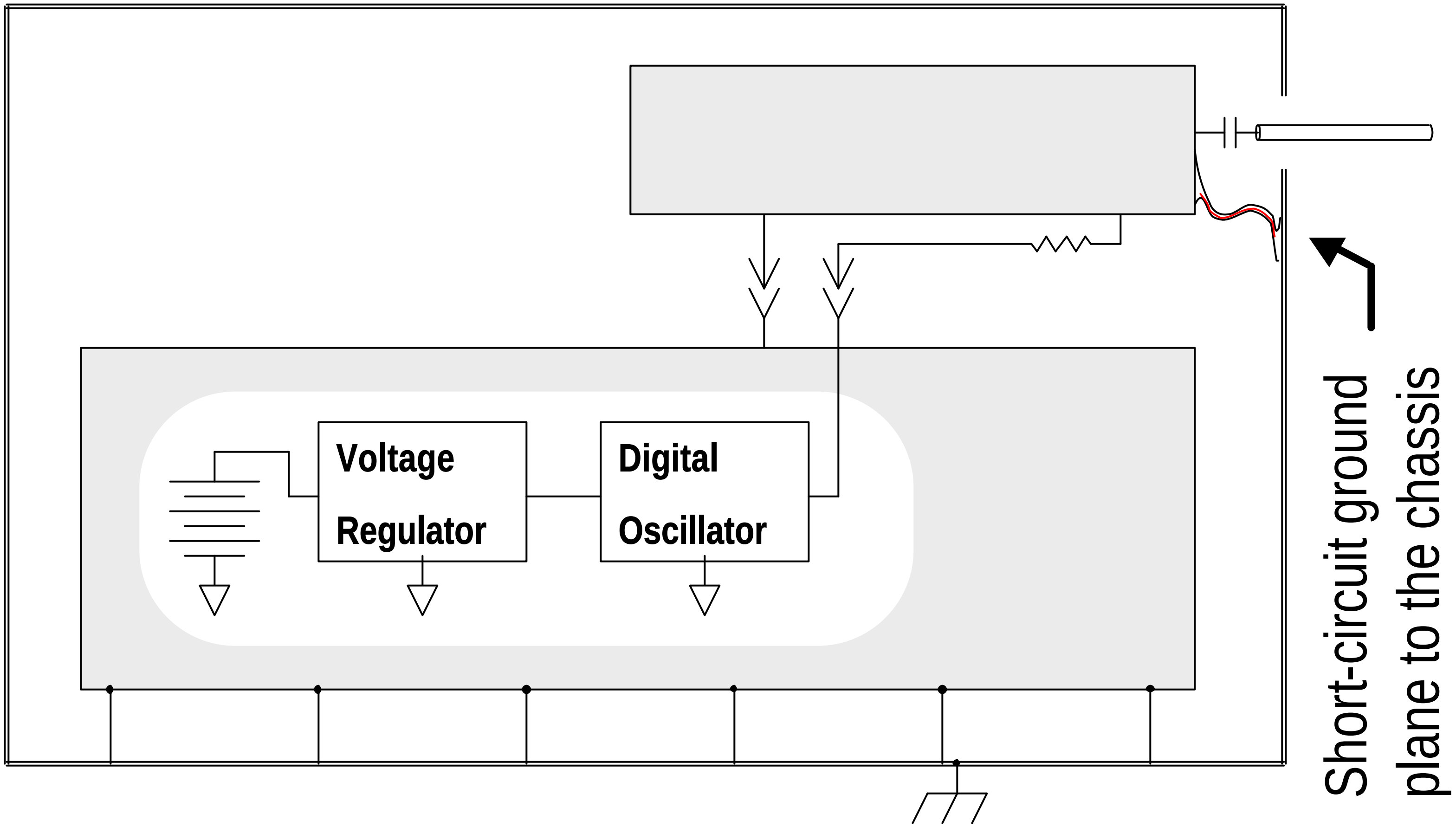
Confirmation of voltage source

Experiment 2B – Shorting PCB to Chassis



Copper Tape Soldered from Chassis
To Daughtercard Groundplane

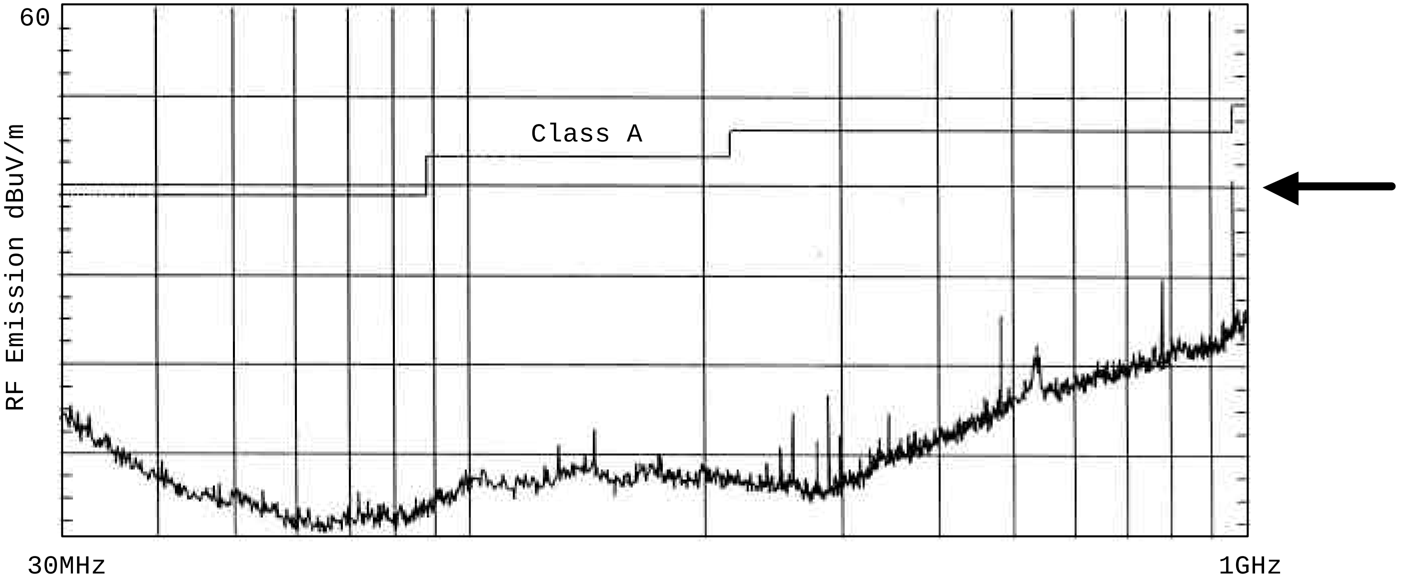
Experiment 2:
Confirm Driving Source

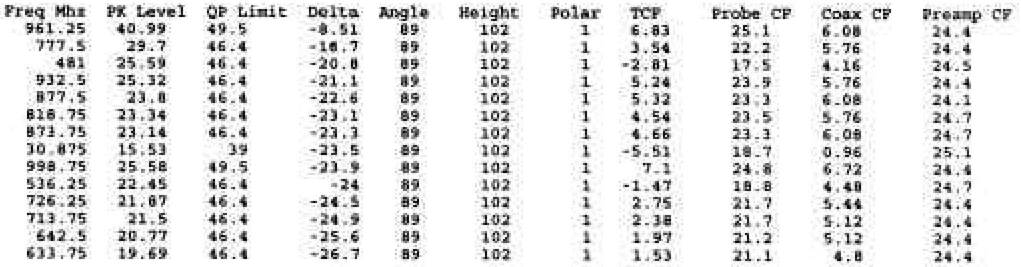


Short-circuit ground plane to the chassis

2A - RF Emission as a Function of *f*

- Repeat of 1C data at 98° - Ground pin only, no tape
- Note strong emissions at 961 MHz

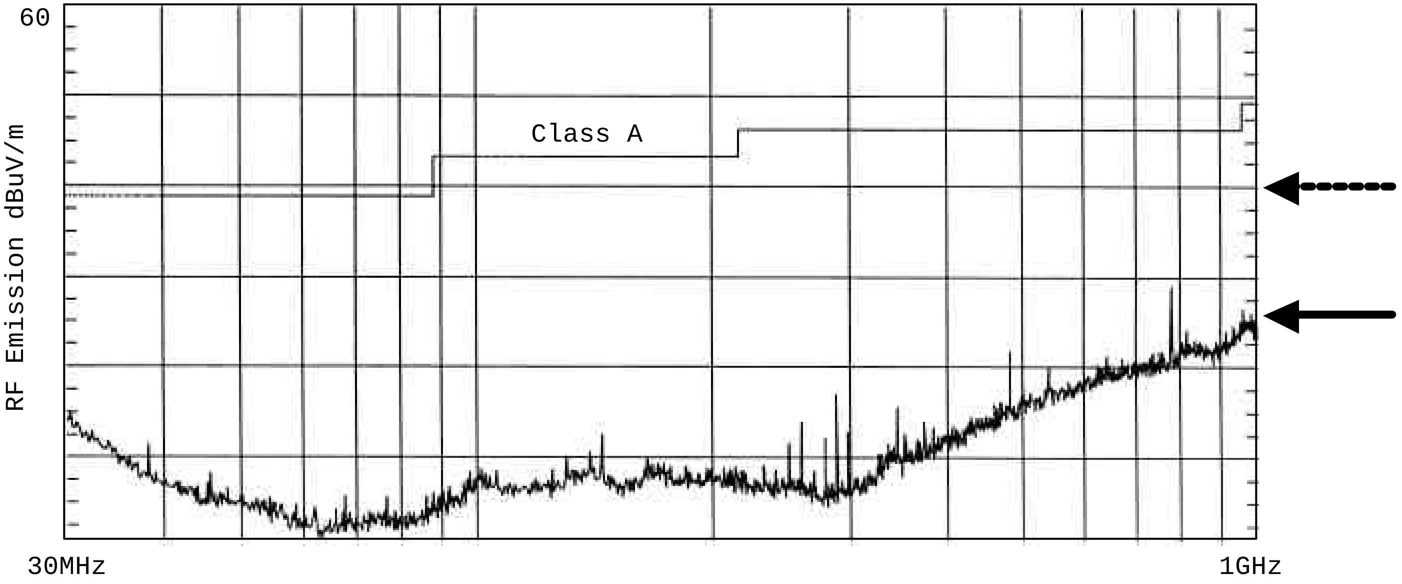


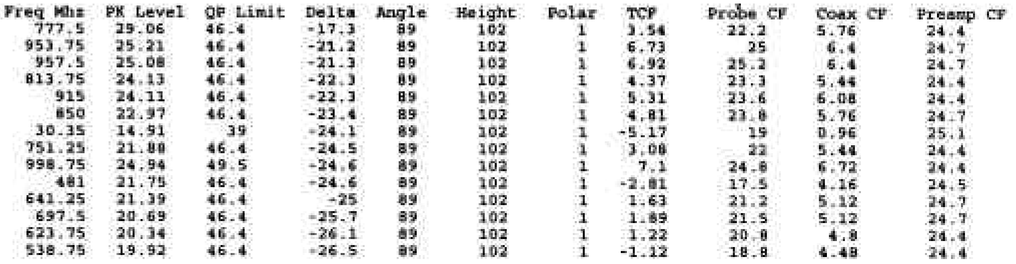


Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCP	Probe CF	Coax CF	Preamp CF
961.25	40.99	49.5	-8.51	89	102	1	6.83	25.1	6.08	24.4
777.5	29.7	46.4	-16.7	89	102	1	3.54	22.2	5.76	24.4
481	25.59	46.4	-20.8	89	102	1	-2.81	17.5	4.16	24.5
932.5	25.32	46.4	-21.1	89	102	1	5.24	23.9	5.76	24.4
877.5	23.8	46.4	-22.6	89	102	1	5.32	23.3	6.08	24.1
818.75	23.34	46.4	-23.1	89	102	1	4.54	23.5	5.76	24.7
873.75	23.14	46.4	-23.3	89	102	1	4.66	23.3	6.08	24.7
30.875	15.53	39	-23.5	89	102	1	-5.51	18.7	0.96	25.1
998.75	25.58	49.5	-23.9	89	102	1	7.1	24.8	6.72	24.4
536.25	22.45	46.4	-24	89	102	1	-1.47	18.8	4.48	24.7
726.25	21.87	46.4	-24.5	89	102	1	2.75	21.7	5.44	24.4
713.75	21.5	46.4	-24.9	89	102	1	2.38	21.7	5.12	24.4
642.5	20.77	46.4	-25.6	89	102	1	1.97	21.2	5.12	24.4
633.75	19.69	46.4	-26.7	89	102	1	1.53	21.1	4.8	24.4

2B - RF Emission as a Function of *f*

- Daughtercard ground plane shorted to chassis
- 961 MHz line has been reduced below noise level





Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCF	Probe CF	Coax CF	Preamp CF
777.5	29.06	46.4	-17.3	89	102	1	3.54	22.2	5.76	24.4
953.75	25.21	46.4	-21.2	89	102	1	6.73	25	6.4	24.7
957.5	25.08	46.4	-21.3	89	102	1	6.92	25.2	6.4	24.7
813.75	24.13	46.4	-22.3	89	102	1	4.37	23.3	5.44	24.4
915	24.11	46.4	-22.3	89	102	1	5.31	23.6	6.08	24.4
850	22.97	46.4	-23.4	89	102	1	4.81	23.8	5.76	24.7
30.35	14.91	39	-24.1	89	102	1	-5.17	19	0.96	25.1
751.25	21.88	46.4	-24.5	89	102	1	3.08	22	5.44	24.4
998.75	24.94	49.5	-24.6	89	102	1	7.1	24.8	6.72	24.4
481	21.75	46.4	-24.6	89	102	1	-2.81	17.5	4.16	24.5
641.25	21.39	46.4	-25	89	102	1	1.63	21.2	5.12	24.7
697.5	20.69	46.4	-25.7	89	102	1	1.89	21.5	5.12	24.7
623.75	20.34	46.4	-26.1	89	102	1	1.22	20.8	4.8	24.4
538.75	19.92	46.4	-26.5	89	102	1	-1.12	18.8	4.48	24.4

Experiment #2 Summary

No.	Angle	Cap	Wire	Shorted	MHz	dBuV/m
2A	89°	10 pF	Yes	No	961	41.0
2B	89°	10 pF	Yes	Yes	961	< 25 *

* measurement limited

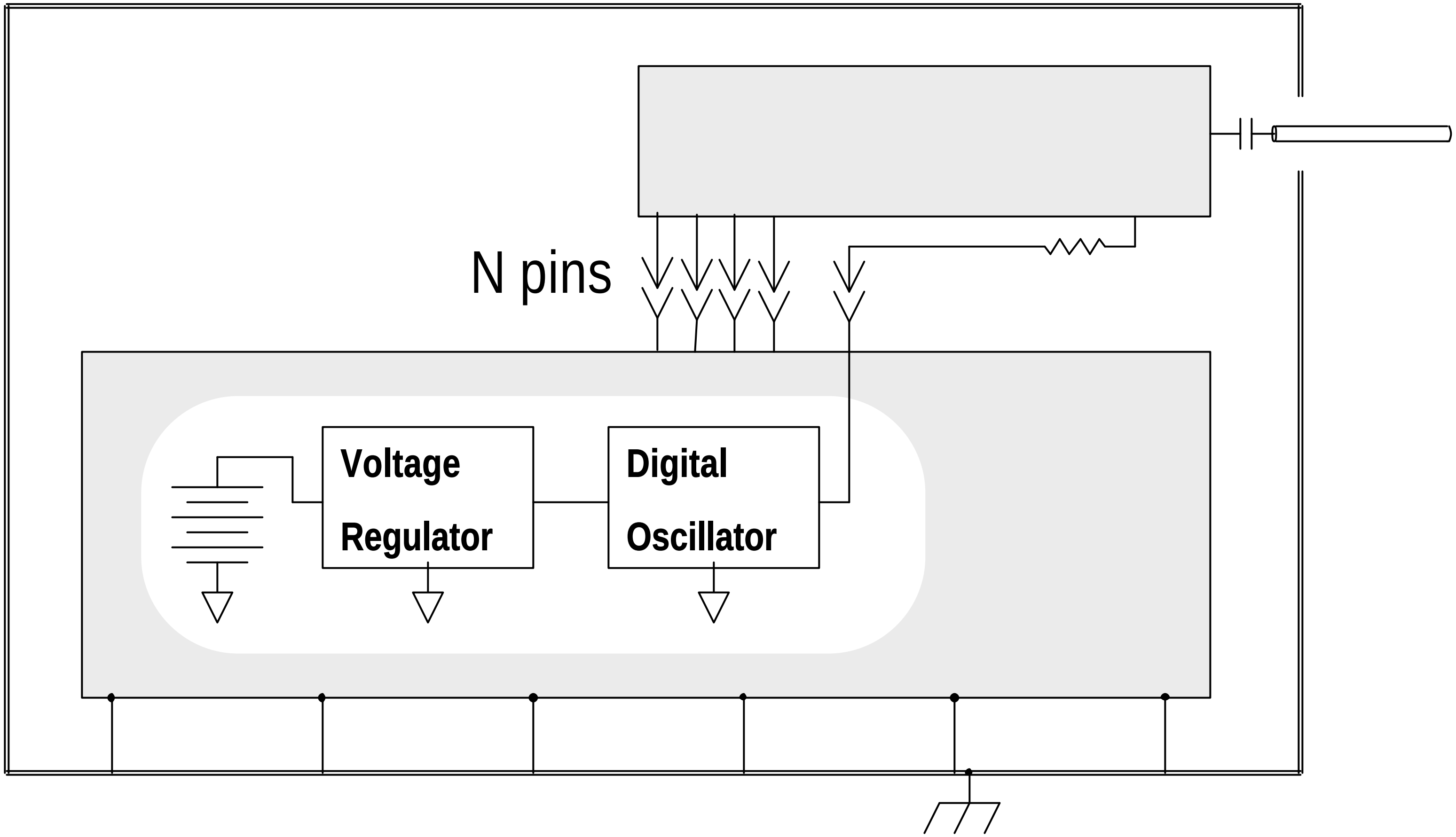
- High frequency voltage on daughtercard groundplane is driving the external metallic body via the capacitor
- Implicates metal parts in fiber optic connectors

Experiment #3

Role of ground pins as ultimate driving source

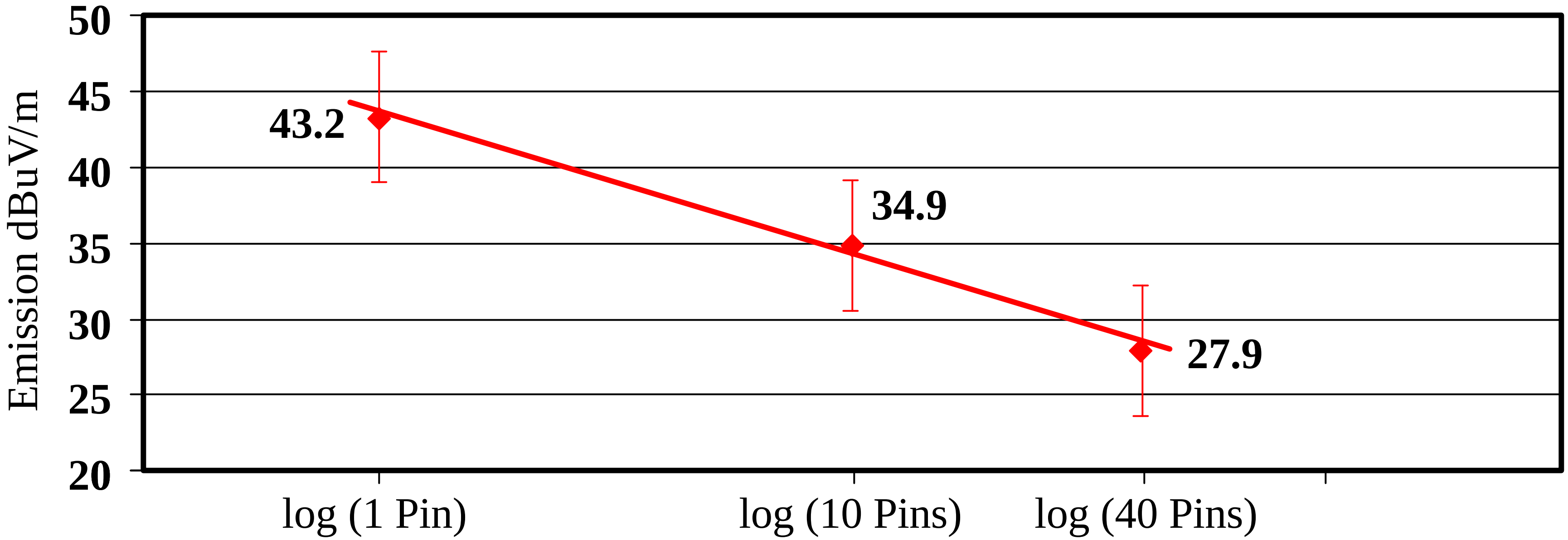
Experiment 3 - Ground Pin Dependence

- Repeat Experiment 1C with more than one ground pin



Maximum RF Emission Values

No.	Signal Pins	Gnd Pins N	MHz	dBuV/m
3A	1	1	961	43.2
3B	1	10	961	34.9
3C	1	40	961	27.9



Experiment #3 Summary

- Parasitic inductance in PCB-to-PCB connectors generates high-frequency potential differences between the daughtercard's groundplane and chassis
- More ground pins correlate with lower amplitude
  - 8dB reduction for 10 ground pins
  - 15 dB reduction for ground 40 pins
- Relationship of RF emissions with respect to N is nonlinear, due to self-inductance, mutual-inductance, and geometric effects
- Problem exacerbated by multiple PCBs and the isolation of "logic ground" from "chassis ground"

Conclusions

The adoption of higher data rates and new technologies can often expose previously hidden non-idealities

Conclusions

- Previously ignored, small metallic parts within optical fiber connectors caused EMC failures in otherwise RF-tight chassis for $f < f_c$
- RF emission is caused by parasitic capacitive coupling of metallic connector parts, via the aperture, to within the otherwise RF-tight chassis
- High-frequency perturbations on daughtercard groundplane, shield, or PCB traces near the aperture provides driving via the parasitic capacitance
- This new, asymmetric, dipole radiates below f_c
- PCB-to-PCB connector inductance implicated

Some Design Practices

- Make apertures as small as physically possible
  - Higher cutoff frequency
  - Reduces parasitic capacitance
- Use conductive septum to divide duplex-SC aperture
- Use conductive dust cover or “trap door” on apertures
- Arrayed apertures will reduce effectiveness
- Limit the amount of conductive materials used in fiber-optic connectors, and anywhere near aperture
- Know your fiber optic cable supplier, and if necessary, specify connectors made from nonconductors
- All optical devices need to be evaluated with the system
- Do not underestimate the mechanical precision required to maintain low-impedance grounding with PCB stacks

Some More Design Practices

- Use numerous ground pins and auxiliary grounding
  - Reduces high-frequency potential differences
  - Better PCB-to-PCB signal integrity
- V_{cc} plane(s) should have ultra-low Z to many GHz
- Shield or isolate high-frequency pads or current loops
- Do not route high-frequency transmission lines on surface
- Control and minimize area of high-frequency current loops
- Follow IC manufacturer’s bypassing instructions
- Minimize daughtercard exposure to aperture
  - Minimize surface area near the aperture
  - Maximize distance to the aperture
- Frontside/backside optical module shielding techniques
- Care should be exercised when isolating logic/chassis ground

Acknowledgements and References

- Acknowledgements
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  - Underwriters Laboratory (formerly C&C Labs)
  - BABT Corporation (formerly Rolm Electronics)
  - Silent Solutions, Alcoa-Fujikura, Emulex, Sun Micro
  - San Francisco State University
  - San Jose State University
- References
  - R. Dahlgren and Z. Tanner, PhoPack 2002 (IEEE-CPMT)
  - K. Masterson, NIST Technical Note #1383 (1997)
  - M. Robinson, IEEE Trans Electromag Compat, V40, N3