Chaos and High Power RF Effects: Statistical Analysis of Induced Voltages

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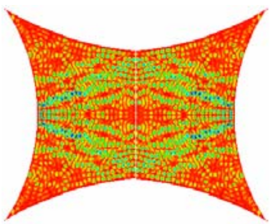

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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH · UNITED STATES AIR FORCE ·

AFOSR Presentation

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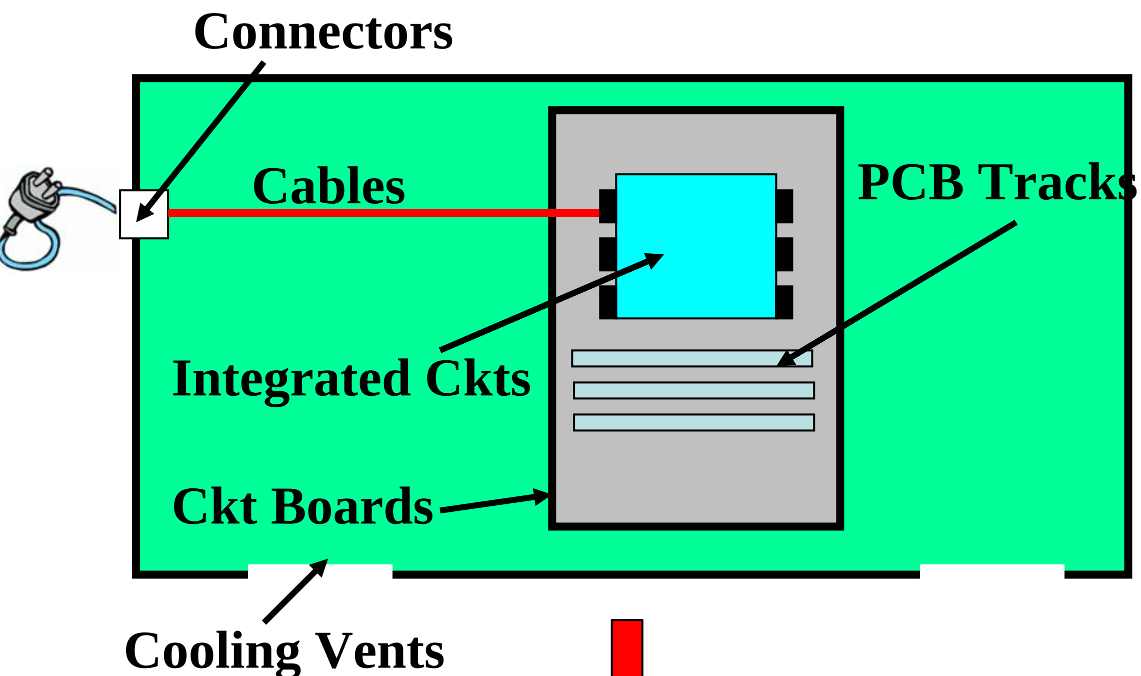
Goal

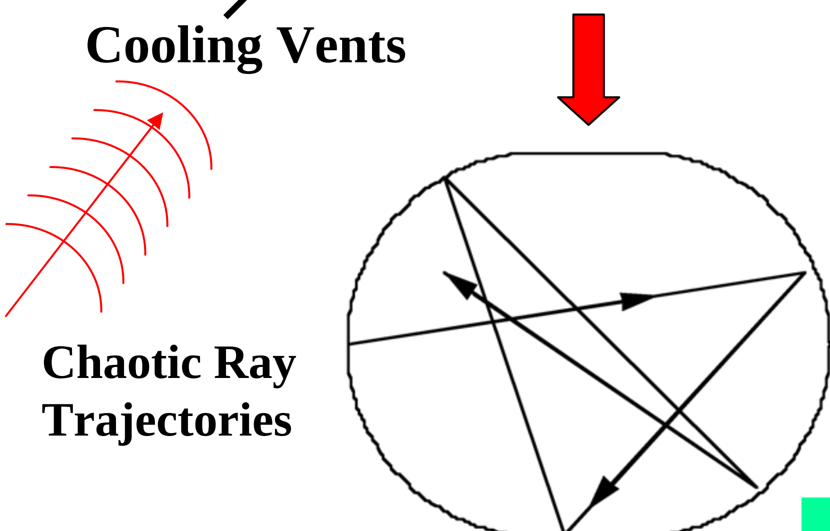
To develop a quantitative statistical understanding of induced voltage and current distributions in circuits inside complicated enclosures, based upon minimal information about the system

HPM Effects:

Electromagnetic Compatibility of Circuits



- Coupling of external radiation to computer chips is a complex process:
  - Apertures
  - Resonant cavities
  - Transmission Lines
  - Circuit Elements
- System Size > Wavelength



We want to understand the scattering properties of this system including the effects of coupling

- Statistical Distribution using Wave Chaos

Why Quantum / Wave Chaos?

Difficulty in making predictions of electromagnetic field structure in complicated enclosures

Predictions can depend sensitively on details

The “soda can problem”

Related work: (Field distributions in reverberation chambers, etc.)

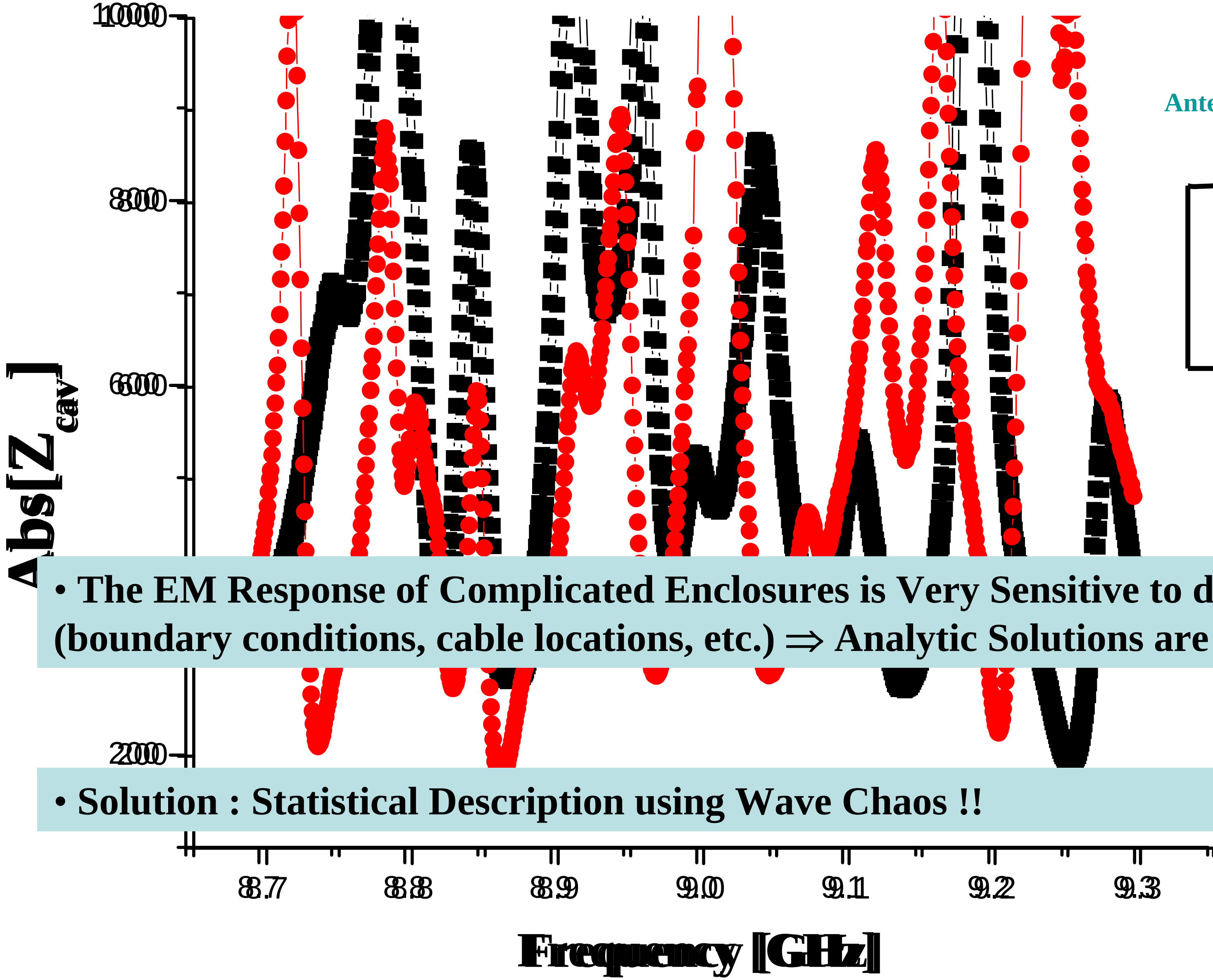
R. Holland and R. St. John, *Statistical Electromagnetics* (Taylor and Francis, Philadelphia, 1999).

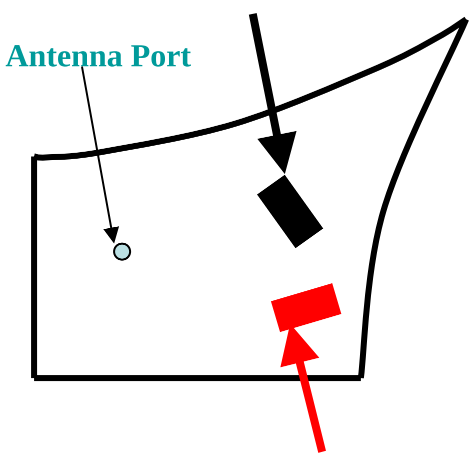
D. A. Hill *et al.*, IEEE Transactions on Electromagnetic Compatibility **36**, 169 (1994).

L. K. Warne *et al.*, IEEE Trans. Antennas Propag. **51**, 978 (2003).

and others…

The Difficulty in Making Predictions…

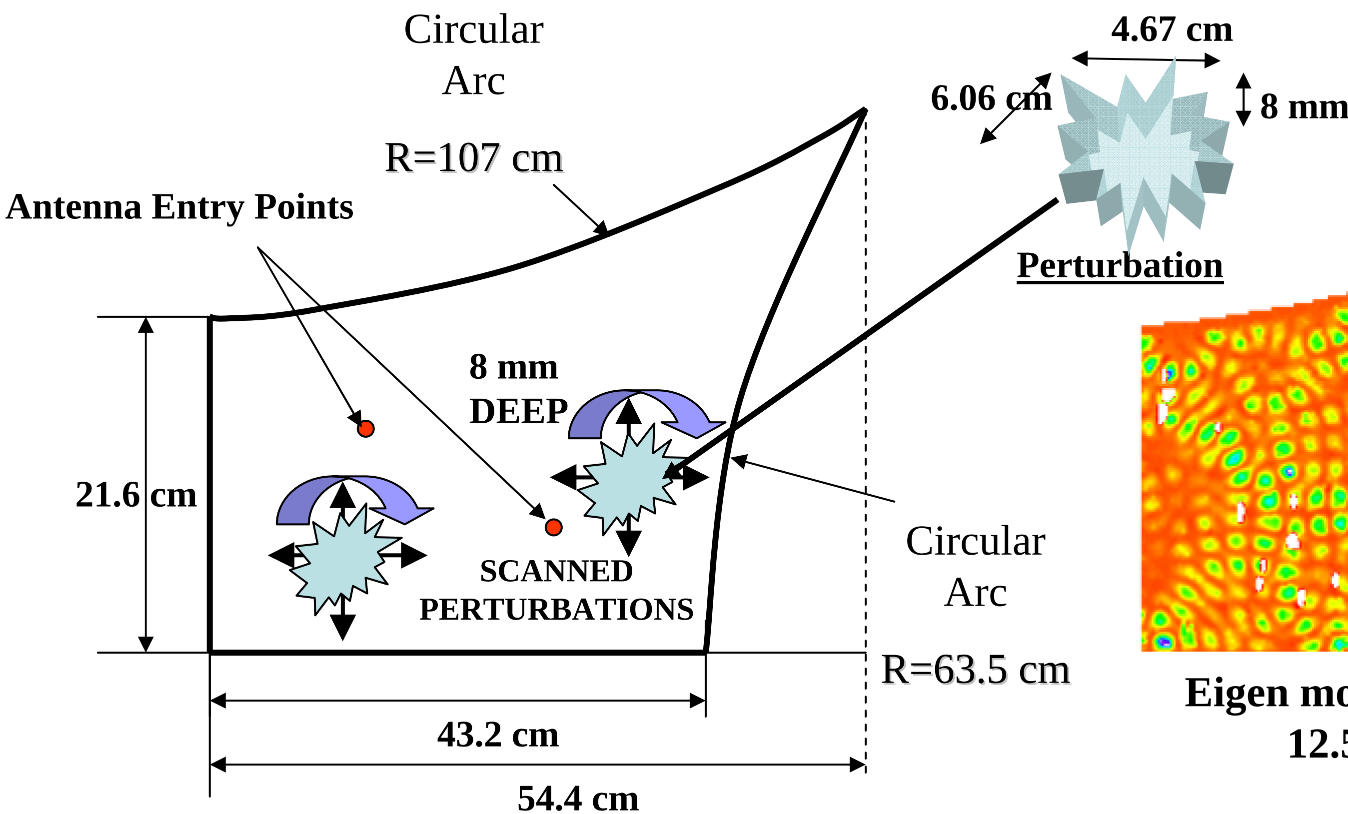


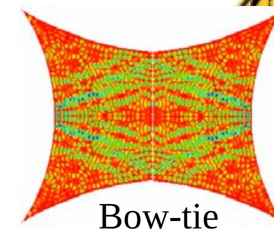


• The EM Response of Complicated Enclosures is Very Sensitive to details (boundary conditions, cable locations, etc.) ⇒ Analytic Solutions are Impractical

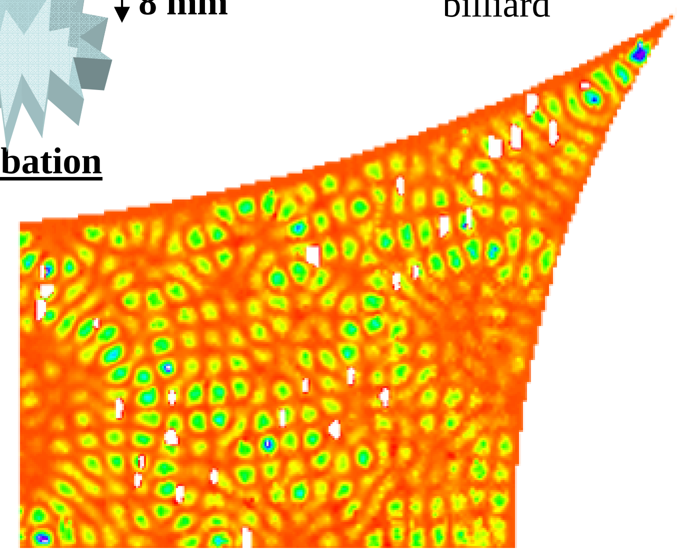
• Solution : Statistical Description using Wave Chaos !!

¼-Bow-Tie Resonator
EXPERIMENTAL SETUP:





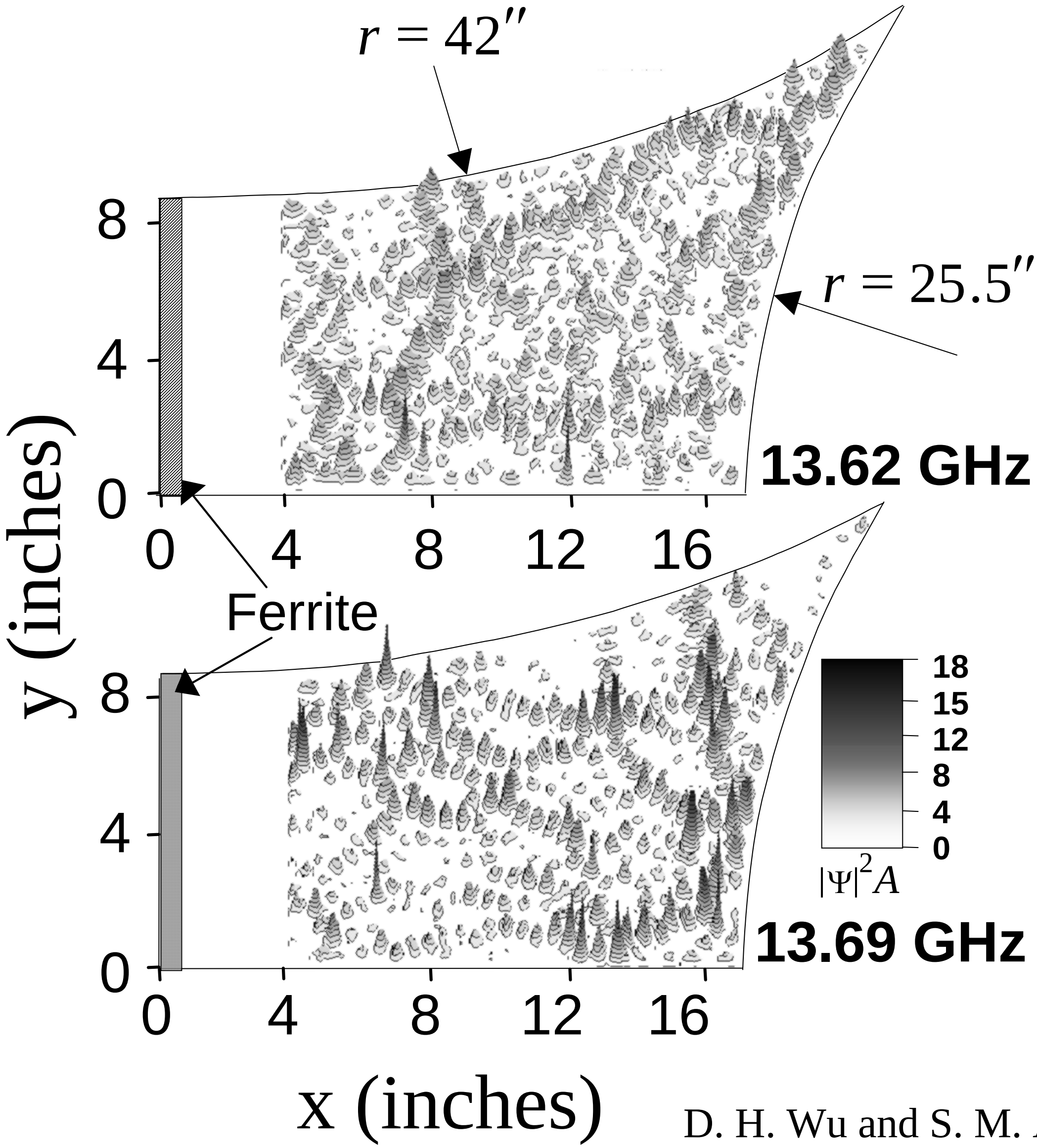
Bow-tie
billiard



Eigen mode Image at 12.57GHz

- 2 Dimensional Quarter Bow Tie Wave Chaotic cavity
- Classical ray trajectories are chaotic - short wavelength - Quantum Chaos
- 1-port, 2-port S and Z measurements in the 3-18 GHz range
- Ensemble average through 100 locations and orientations of the perturbations
- Perturbers are of size ~λ or bigger

Wave Chaotic Eigenfunctions



Uncover simple statistical properties of:

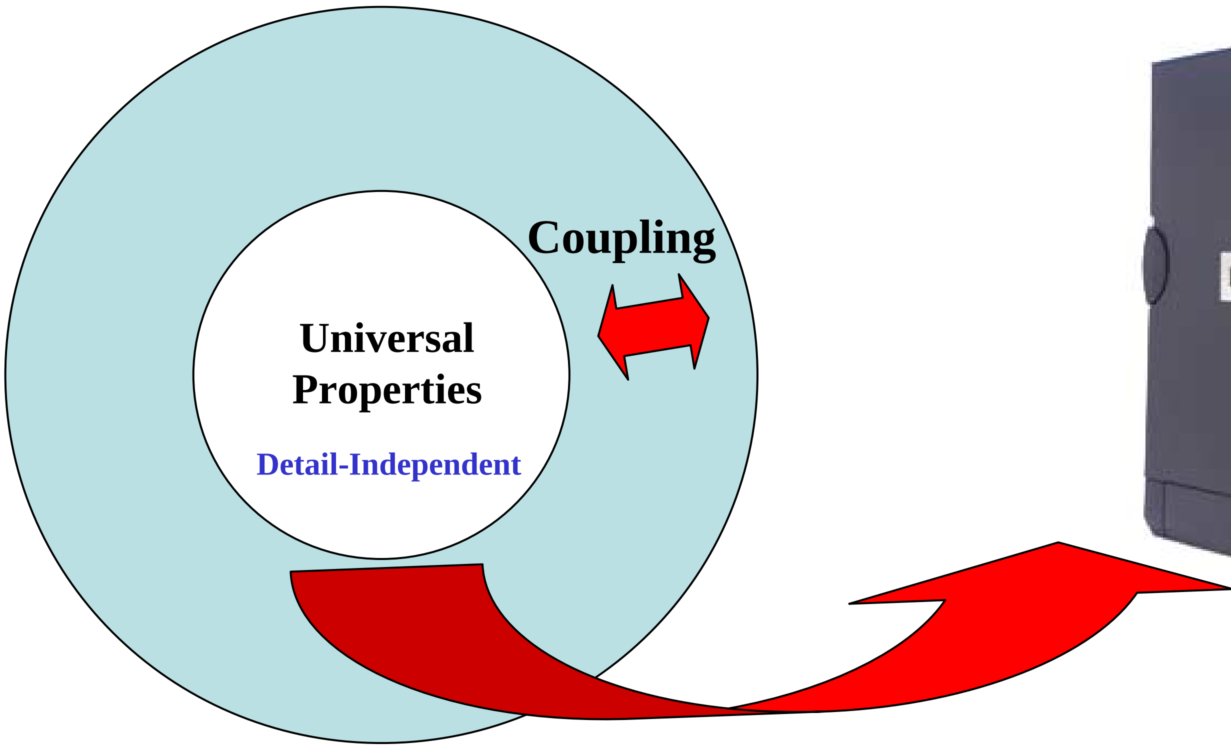
Eigen-frequencies,
Eigen-functions,
Scattering matrix,
Impedance matrix,
Admittance matrix,
etc.

Many of these simple statistical properties are described by Random Matrix Theory

D. H. Wu and S. M. Anlage,
Phys. Rev. Lett. 81, 2890 (1998).

Practical Implications for Real Life Problems

Bare Minimum Specifications for Induced-Voltage Statistics



Statistical EM Response of real enclosures

What are the bare minimum specifications to accurately predict voltage Statistics?

Minimum Information:

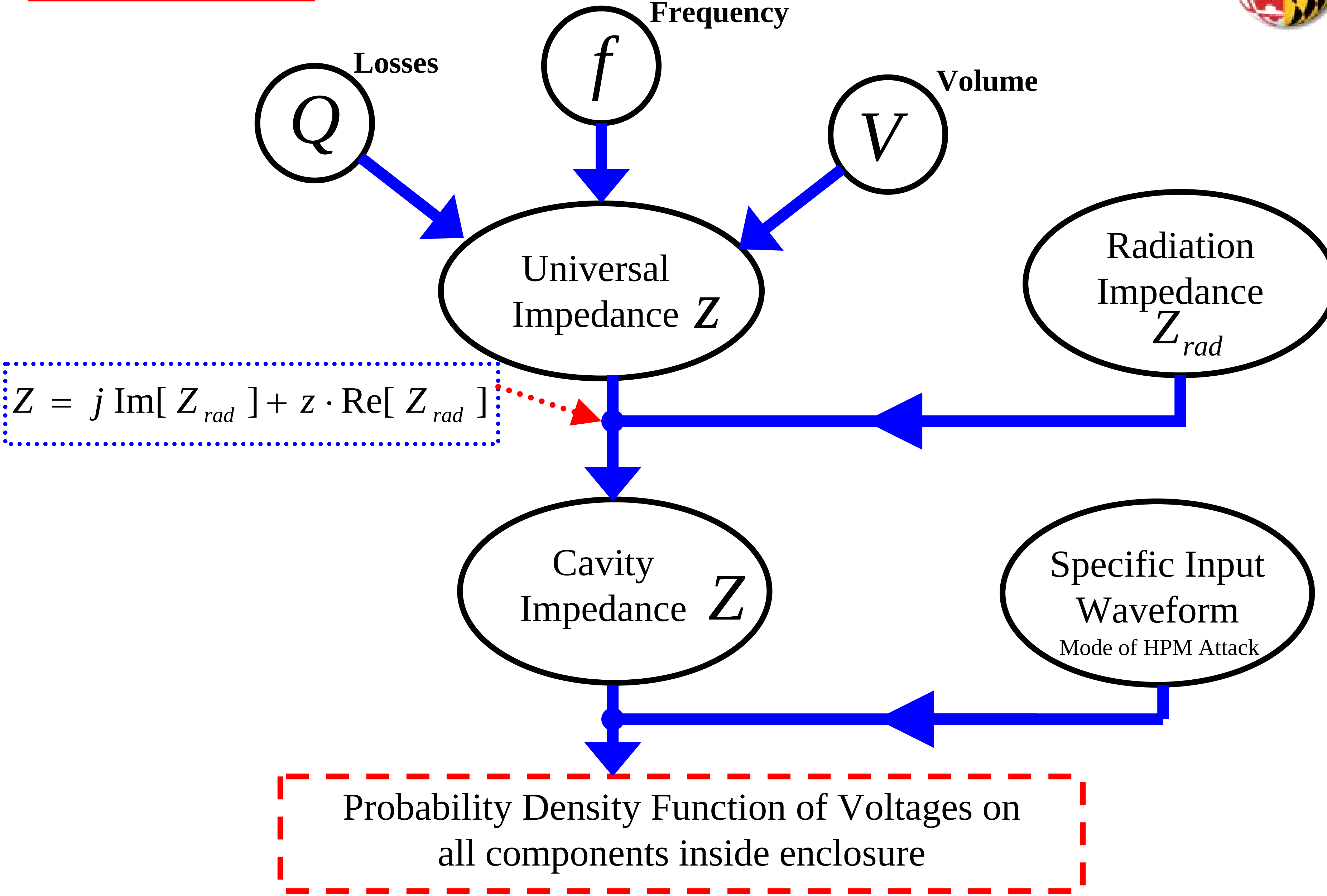
Frequency, Volume and Losses

Radiation impedance of the ports

Determine the "Key Parameter" $\frac{k^2}{\Delta k_n^2 \cdot Q}$

Determines the shape and scales of cavity Z and S PDFs.

Algorithm for Predicting Component Induced-Voltage Distributions:



Prescription to Engineer Cavities with Desired Electromagnetic Properties: Simple 1-Port Example

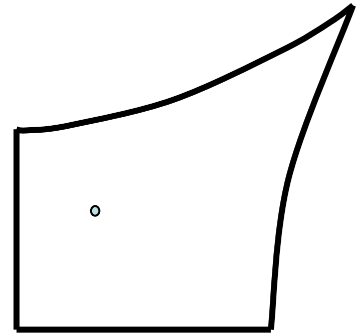
Numerically Generated (z)

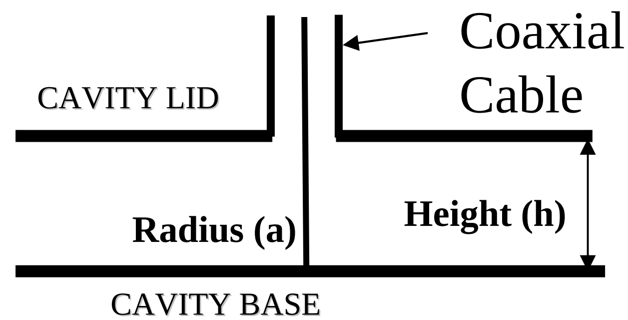
Depends only upon $\dfrac{k^2}{\Delta k_n^2 \cdot Q}$

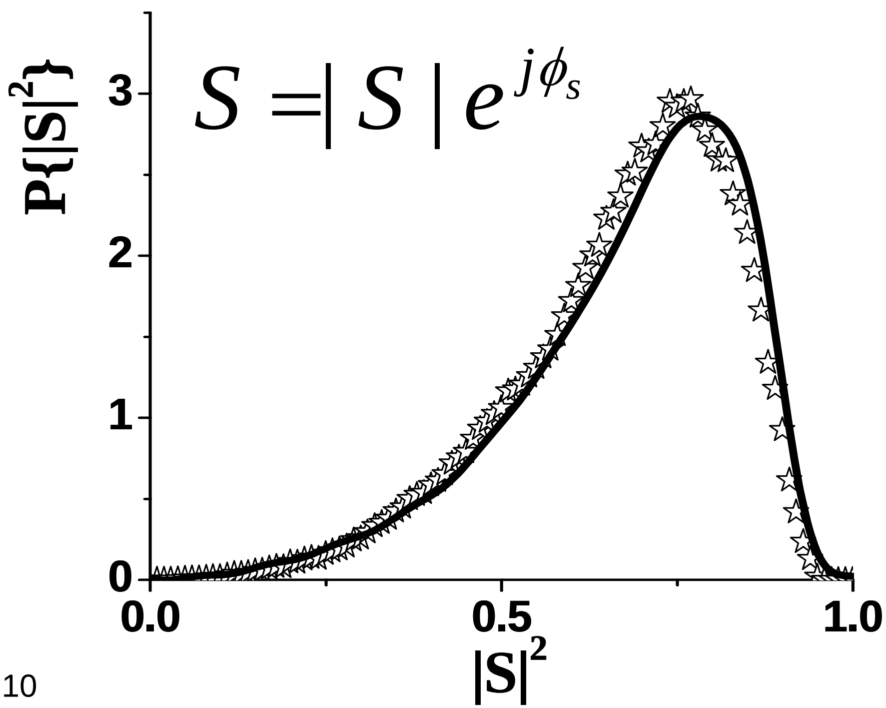
$$Z_{cav} = jX_{rad} + z \cdot R_{rad}$$

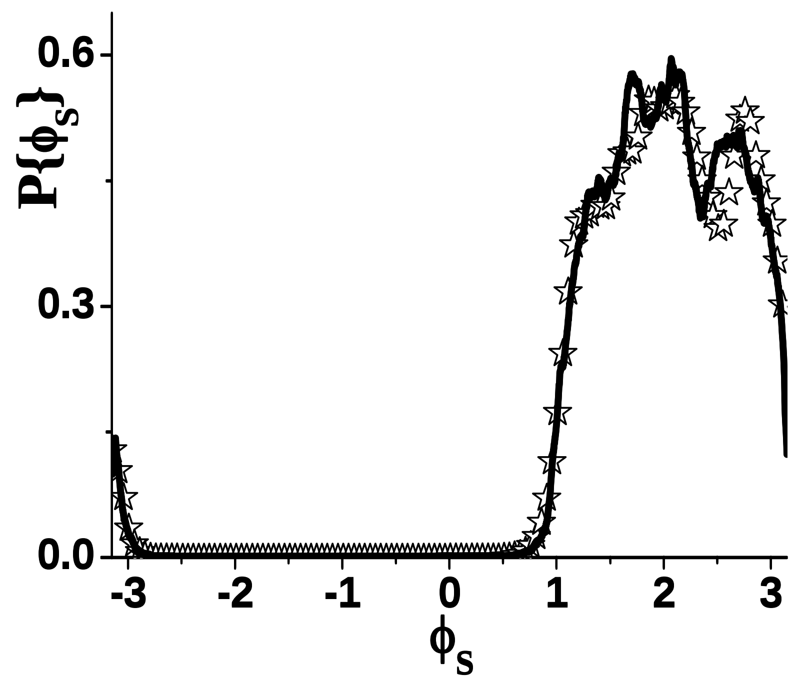
$$Z_{rad} = R_{rad} + jX_{rad}$$

- **Freq : 6 to 9.6 GHz**
- **Antenna Dia (2a)= 1.27mm**



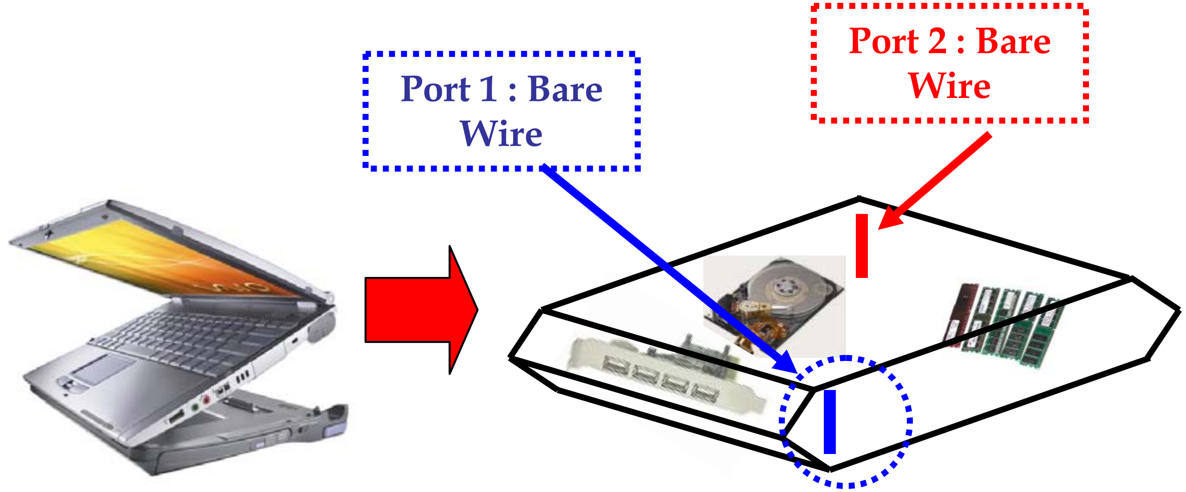


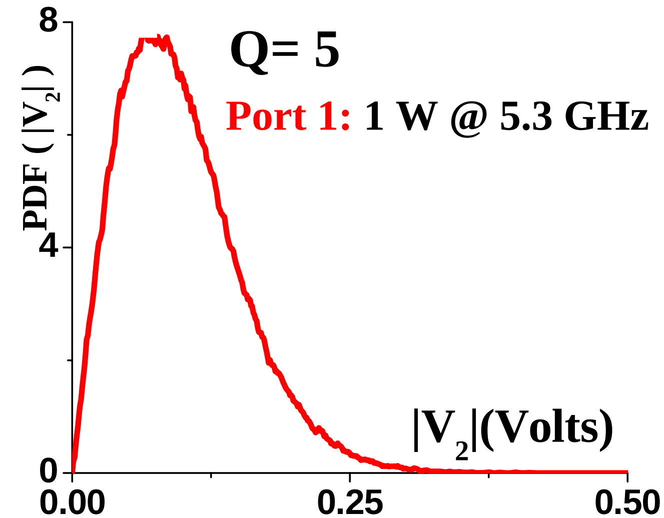




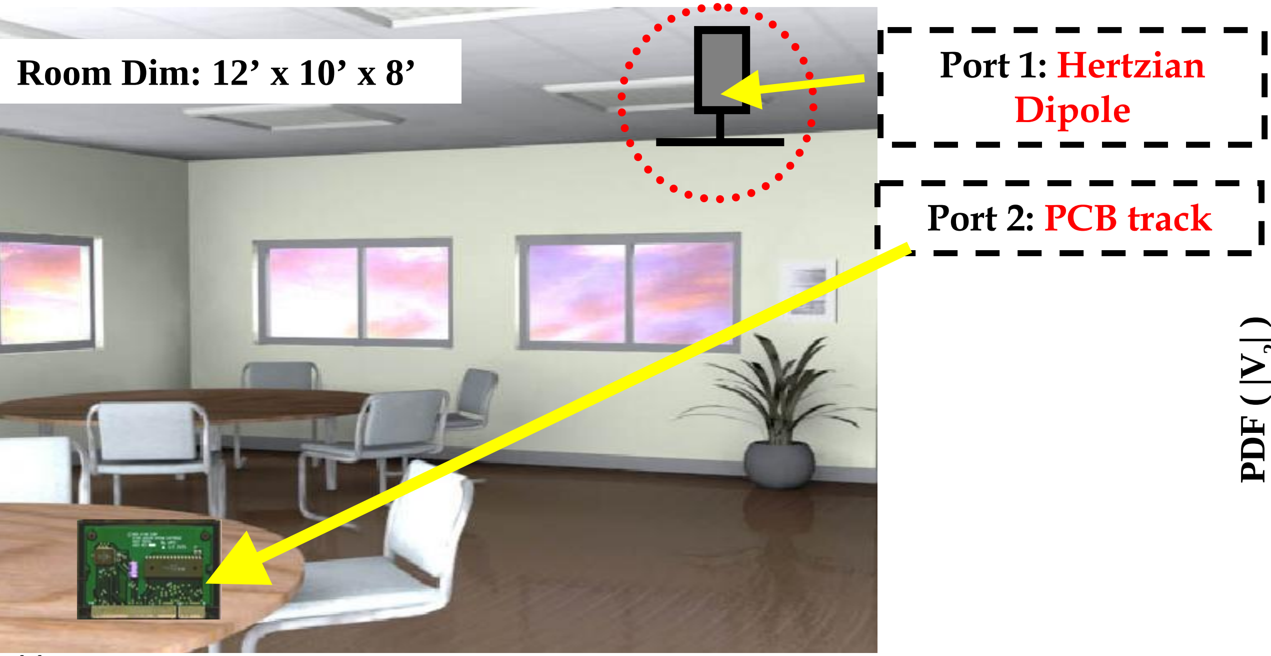
Application of RCM to a Real Problem

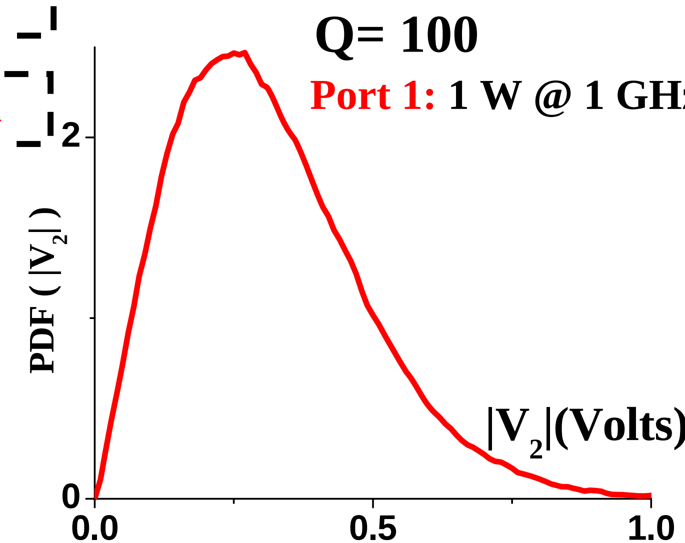
Induced Voltage PDFs in a Computer Enclosure and Room





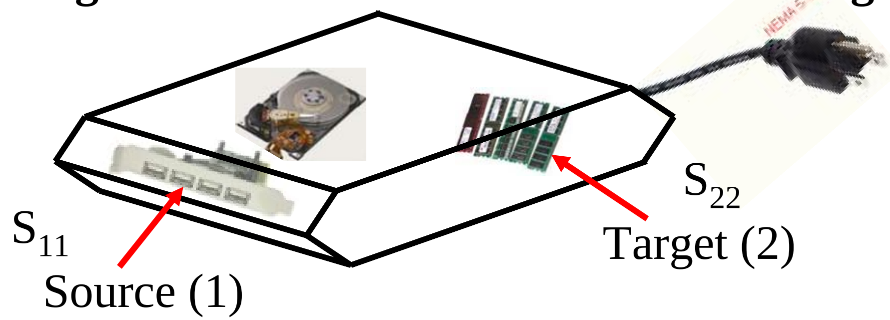
Laptop Dim: 0.24m x 0.27m x 0.04m

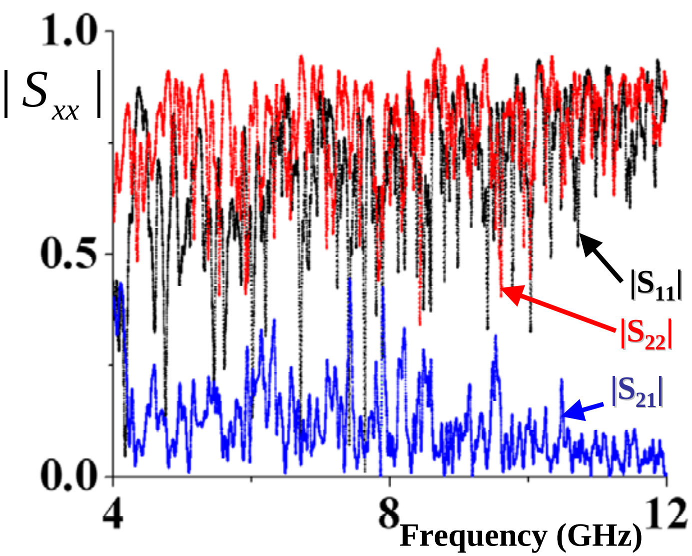


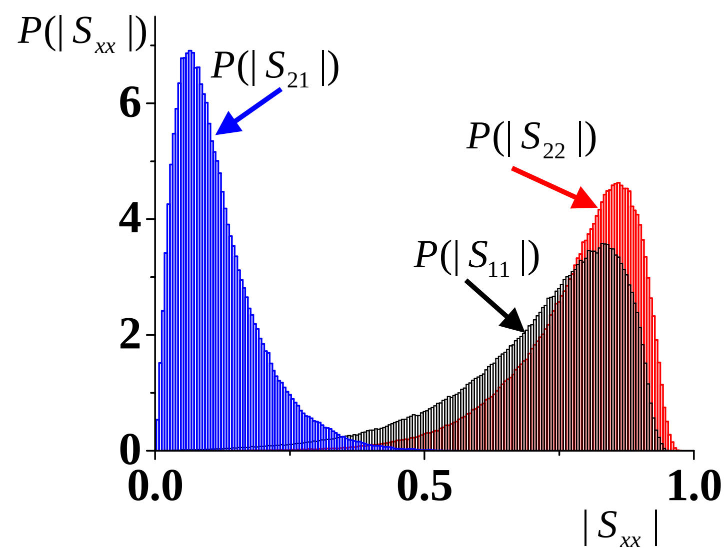


Variance of Voltage and Current Distributions on the Target

Given the variance of S_{11} and S_{22}, we can predict the variance of the induced voltage and current distributions in the target







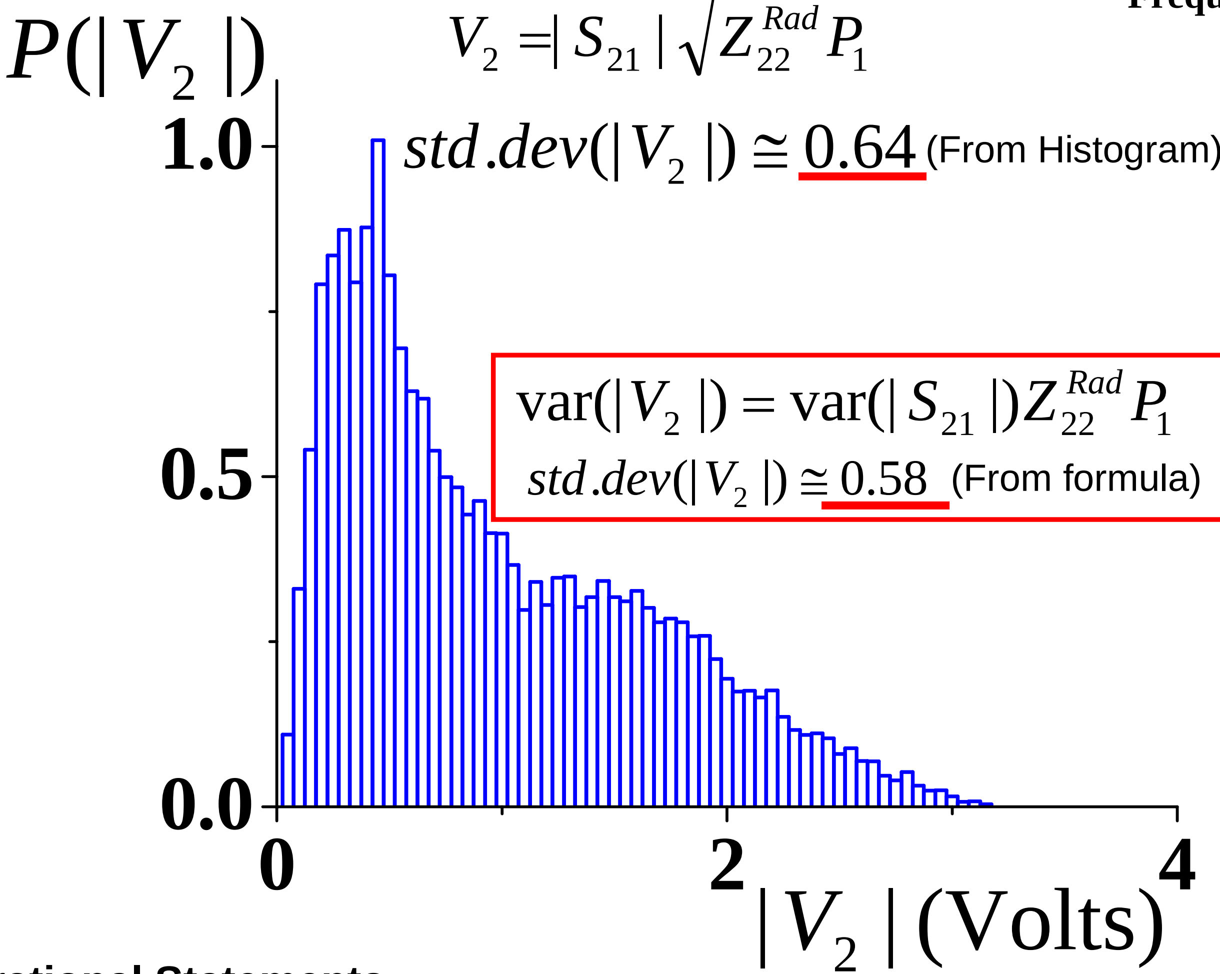
$$Var(S_{12}) \approx \frac{1}{2}\sqrt{Var(S_{11})Var(S_{22})} \quad \text{(ONERA)}$$

Or even better: $$Var(Z_{12}) = \frac{1}{2}\sqrt{Var(Z_{11})Var(Z_{22})} \quad \text{(Maryland)}$$

PDF of Induced Voltages on Port 2 with 1 Watt Radiated by port 1:

Frequency: 5-6 GHz.

$$V_2 = |S_{21}| \sqrt{Z_{22}^{Rad} P_1}$$



$$std.dev(|V_2|) \cong 0.64$$ (From Histogram)

$$\mathrm{var}(|V_2|) = \mathrm{var}(|S_{21}|) Z_{22}^{Rad} P_1$$

$$std.dev(|V_2|) \cong 0.58$$ (From formula)

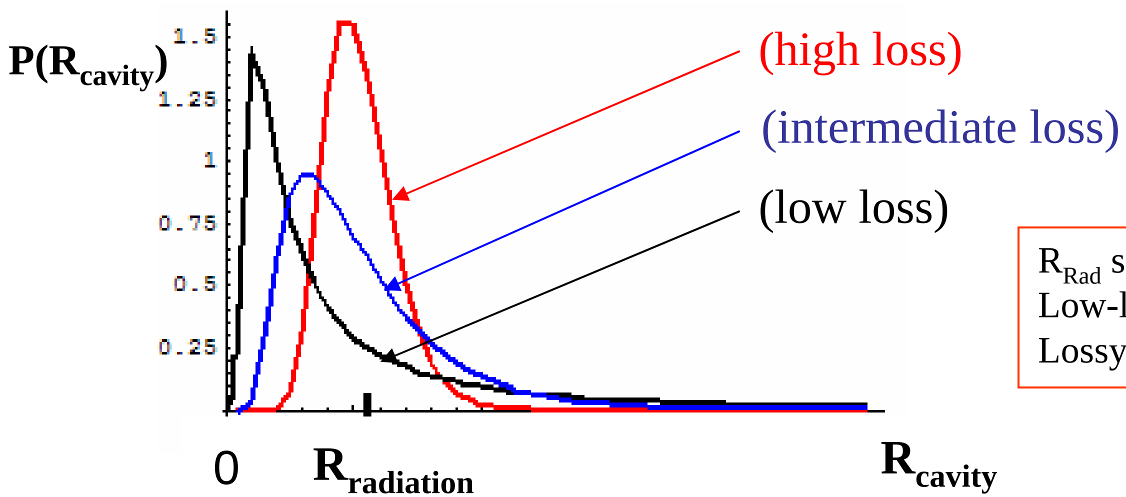
Operational Statements:

Measure Var(Z_{11}) of the target to quantify its degree of susceptibility to HPM attack

Minimizing Var(Z_{11}) of the target is a strategy for minimizing damage from HPM attack

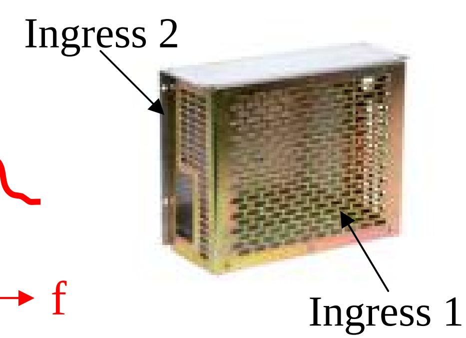
Cavity Impedance and Field PDF Engineering

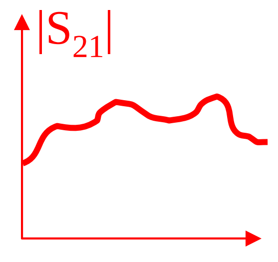
RCM Results

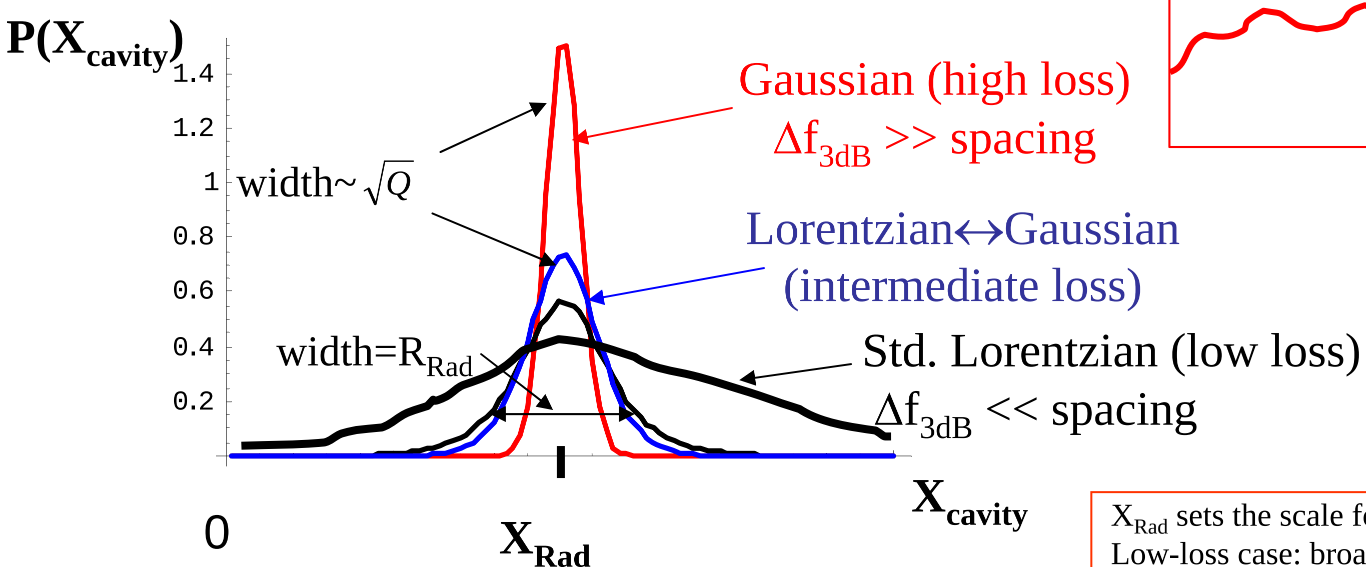


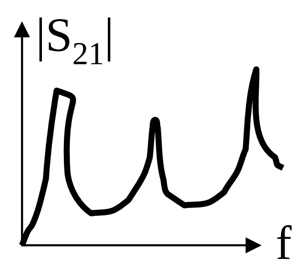
$$Z_{cavity} = R_{cavity} + i\, X_{cavity}$$

R_{Rad} sets the scale for R_{cavity}
Low-loss case: $R_{Cavity} < R_{Rad}$
Lossy case: ⇒ Gaussian distribution, width ~ $\sqrt{Q}$









X_{Rad} sets the scale for X_{cavity}
Low-loss case: broad tails, width ~ $R_{Radiation}$
Lossy case: narrow distribution, width ~ $\sqrt{Q}$

Conclusions

Deterministic measurements (or calculation/simulation) of the radiation impedance remove the effects of coupling to recover universal statistical electromagnetic properties

Experimental tests of many basic 1 port and 2-port predictions have confirmed that the approach is correct.

Frequency, Volume
Losses } $\dfrac{k^2}{\Delta k_n^2 Q}$
Radiation impedance of the ports } Determine the Z, S PDFs

Proposed a universal relation for impedance variances in 2-port systems

Clear strategies to engineer the PDFs to suit one's purpose

S. Hemmady, *et al*., Phys. Rev. Lett. 94, 014102 (2005)
X. Zheng, *et al*., J. Electromag. 26, 3 (2006)
X. Zheng, *et al*., J. Electromag. 26, 37 (2006)
S. Hemmady, *et al*., Phys. Rev. E 71, 056215 (2005)
X. Zheng, *et al*.: submitted to Phys. Rev. E, cond-mat/0504196

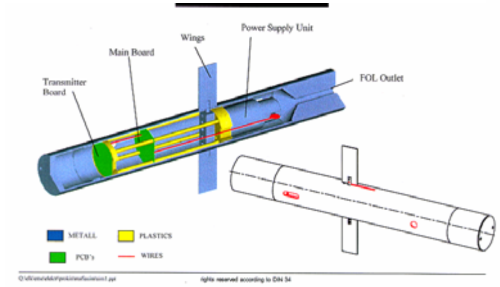
Our Vision for the Future…

• **Random Coupling Model shows very promising signs... But still in its infancy.**

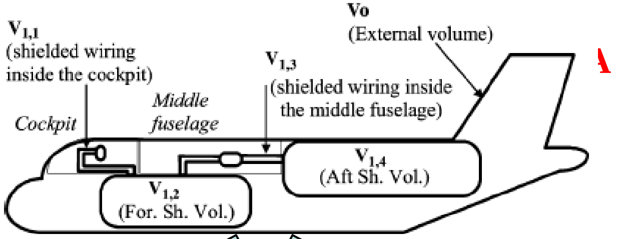
• **Experimentally Validate RCM in realistic 3D environments:**

• GENEC device
• Mode-Stirred Chambers at ONERA
• Realistic antenna configurations (apertures, bundle of cables, etc.)
• Non-Reciprocal Media as a way to mitigate EM "Hot Spots" –Darmstadt-Germany

GENEC Hardware



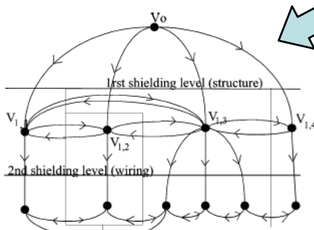
• **Transfer the Model and it's predictive capabilities to the END User:**
  • Document the strengths and weaknesses of the model
  • Demonstrate it's utility (User's Guide)
  • Educate the User in the strategy and execution of predictions



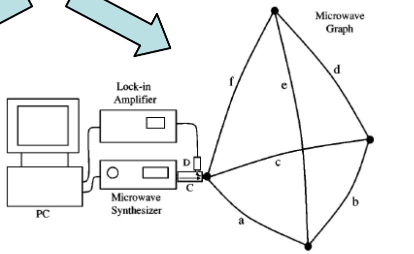
• **Extend RCM to Pulsed Time-Domain Measurements:**

  • Compelling Theoretical Work initiated – Hart, Antonsen, Ott

• **Connect RCM to the EM Topology Approach:**
  •Quantum graphs and chaos on networks



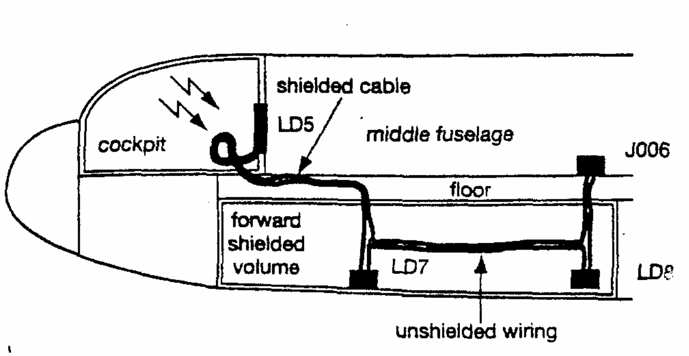
EMC topology



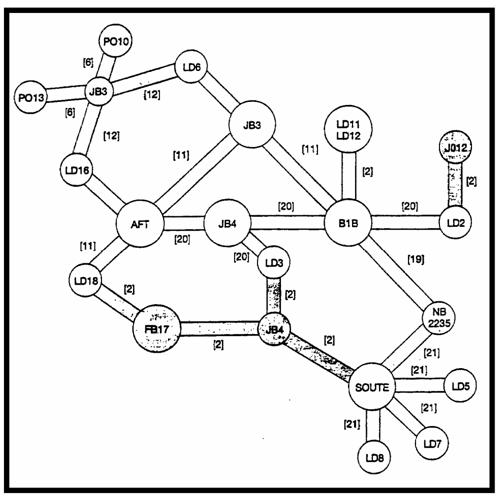
Quantum Graphs

EMC Topology and CRIPTE– *Baum, Liu, Tesche, Parmantier*

Aircraft and cable configuration



Network topology



• **For really complex systems, a small change in frequency, orientation of EM features can result in vastly different internal field configurations.**

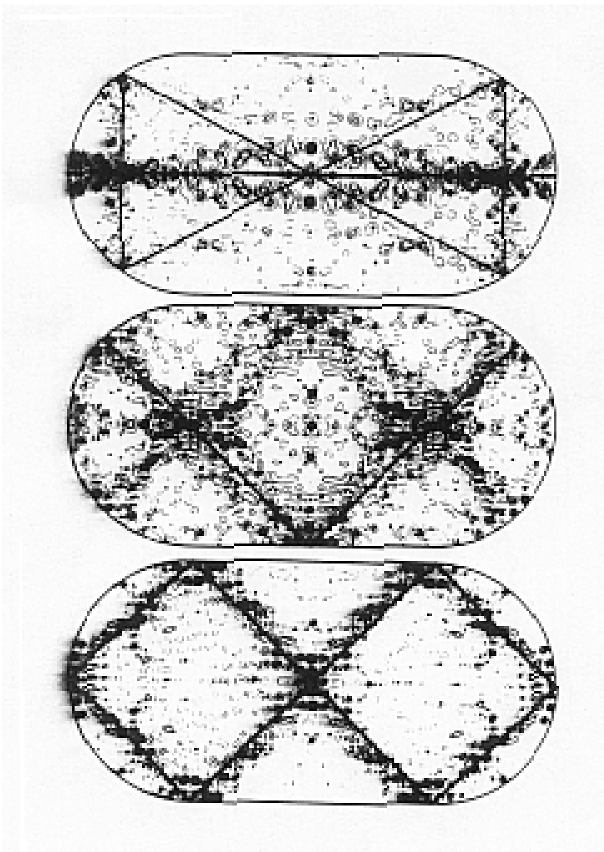
•Need for a Statistical Approach

† **Parmantier, J-P-*IEE Computing & Control Engineering Journal*, April 1998.**

Some Other Future Plans

Consider the effects of objects inside the enclosure

Scars
Refraction and "Freak Waves" } **Very large amplitude waves**



SCARS (Heller, 1984)

Concentrations of wave density along unstable periodic orbits.

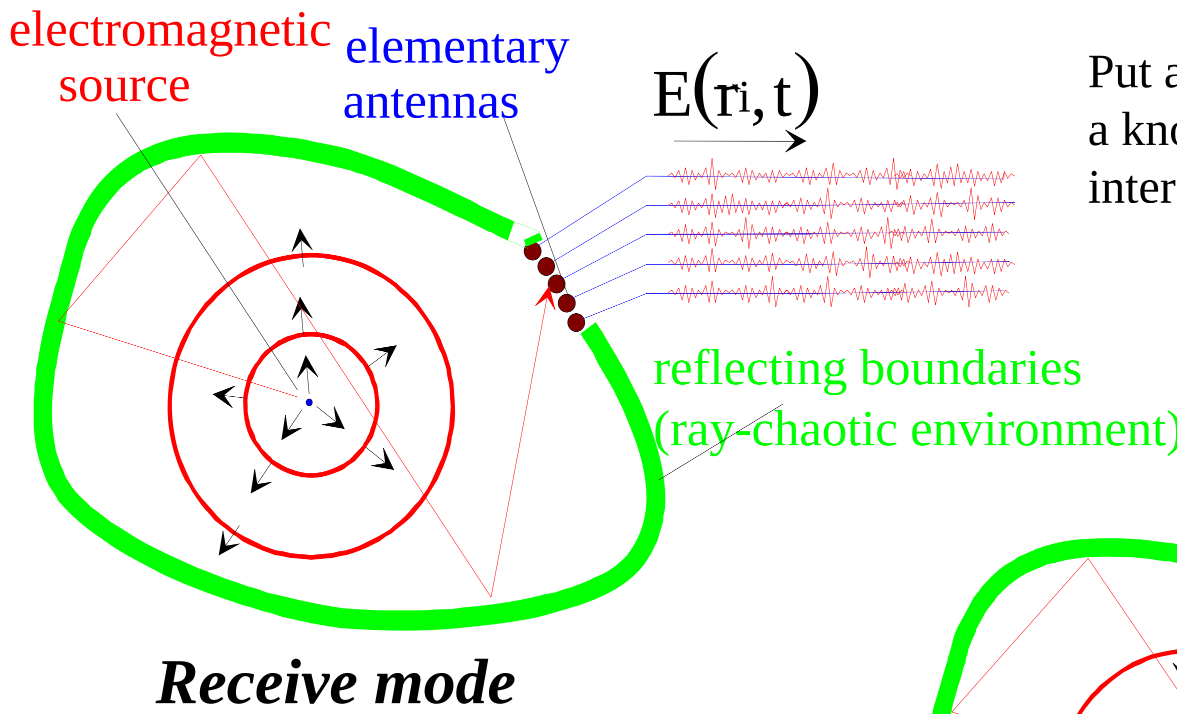
Quantum counterpart to classical phase space density is not uniform on the energy surface.

Study of <u>mixed</u> dynamics (Chaotic and regular)

What can be done with Time-Reversed Electromagnetics? Combine with Chaos to do new things

Deliver a localized "Electromagnetic Punch"

Put a source emitting a pulse or a known signal at the location of interest



Time-reverse, <u>amplify</u> and broadcast the coda