Quantitative Understanding of Induced Voltage Statistics for Electronics in Complex Enclosures

COST MC Meeting, Toulouse, France

13 February, 2017

ACCREDIT ACTION IC 1407

IC1407 Advanced Characterisation and Classification of Radiated Emissions in Densely Integrated Technologies (ACCREDIT)

MANAGEMENT COMMITTEE MEETING

Toulouse, France

13 - 14 February 2017

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Random Coupling Model website: http://anlage.umd.edu/RCM

Research funded by ONR

ONR/DURIP

AFOSR / AFRL Center of Excellence

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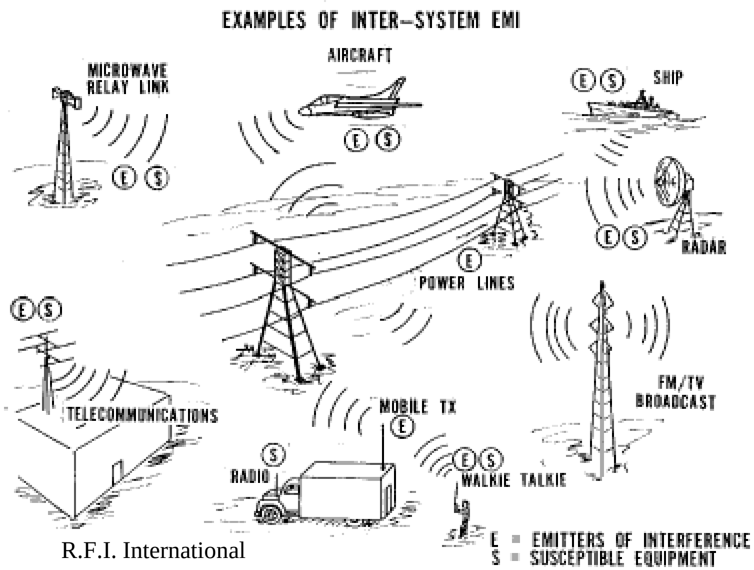
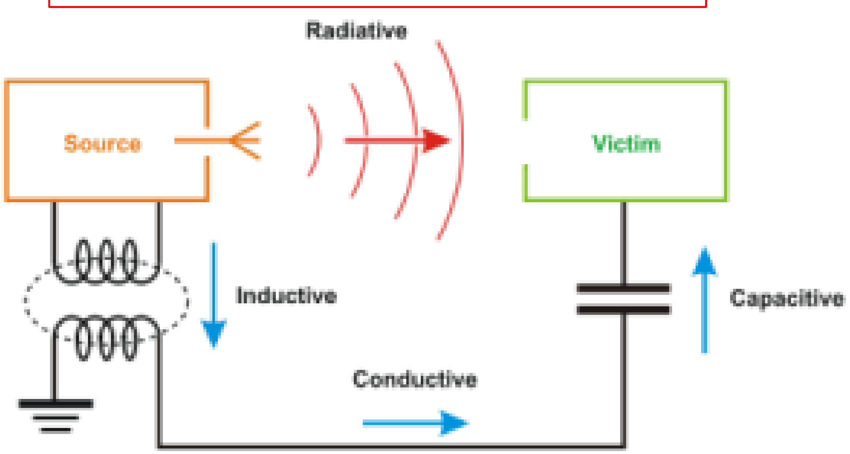
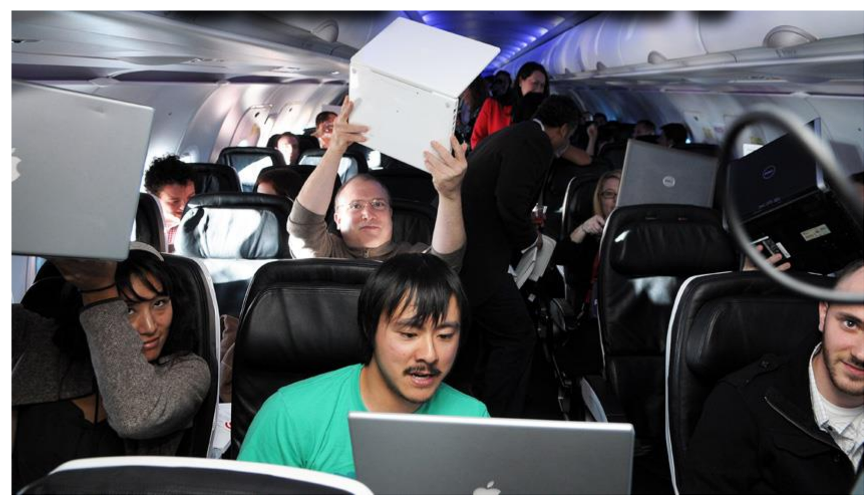
Electromagnetic Interference and Electronics

How to defend electronics from electromagnetic interference?



Electromagnetic Interference (EMI)
Electromagnetic Compatibility (EMC)

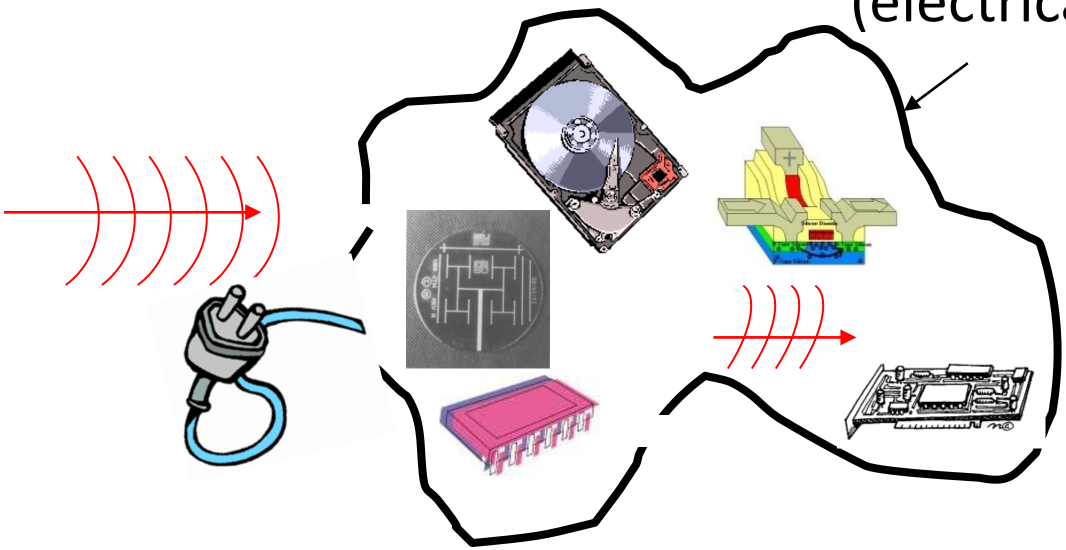




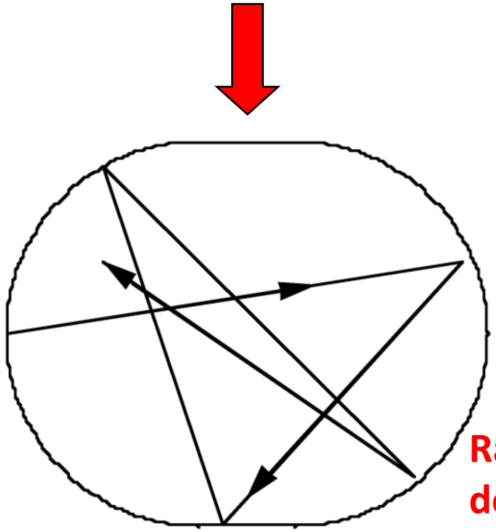
Electromagnetic Coupling to Enclosures and Circuits

A Complicated Problem

Arbitrary Enclosure
(electrically large, with losses “1/Q”)



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



Chaotic Ray Trajectories

What can we say about the nature of fields and induced voltages inside such a cavity?

- Statistical Description using Wave Chaos!!

Rather than make predictions for a specific configuration, determine a probability distribution function (PDF) of the relevant quantities

Outline

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- Our Approach – A Wave Chaos Statistical Description
- The Random Coupling Model (RCM)
- Example of the RCM in Practice
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- Extension of the RCM to Stochastic Sources
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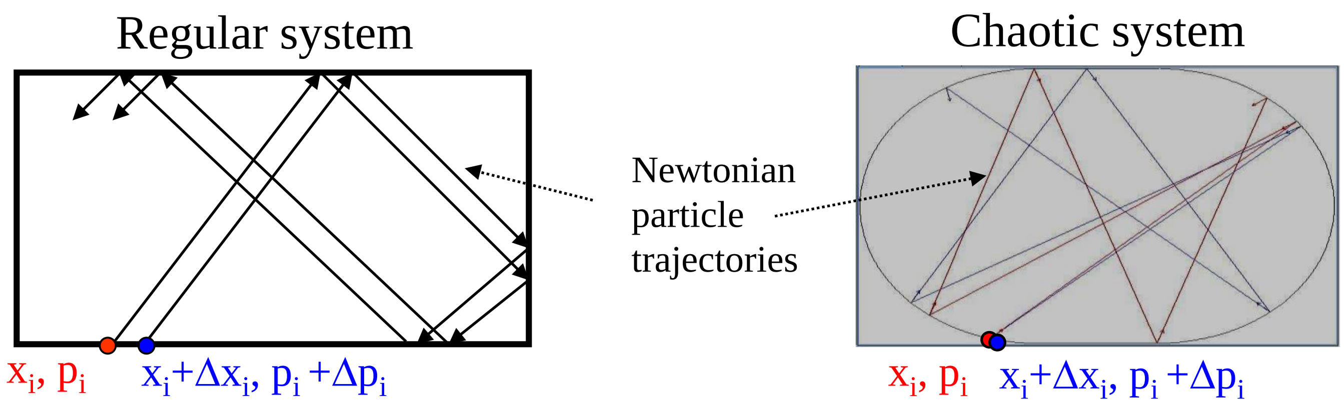
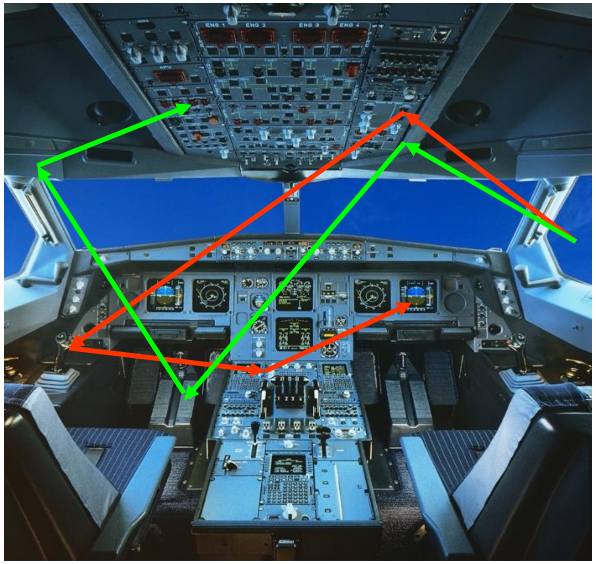
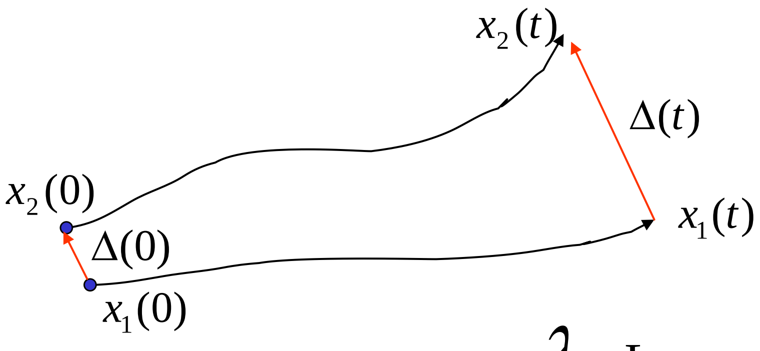
Classical Chaos in Newtonian Billiards

Best characterized as "extreme sensitivity to initial conditions"





2-Dimensional "billiard" tables



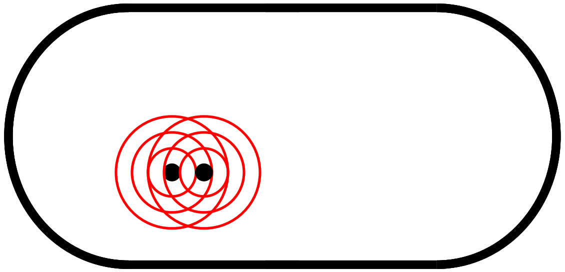
$$\Delta(t) = \Delta(0)\, e^{\lambda t}$$

$$\lambda > 0$$

λ Lyapunov exponent

Wave Chaos?

1) Waves do not have trajectories



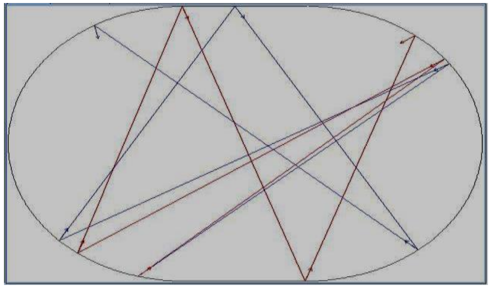
It makes no sense to talk about "diverging trajectories" for waves

2) Linear wave systems can't be chaotic

Maxwell's equations, Schrödinger's equation are linear

3) However in the semiclassical limit, you can think about rays

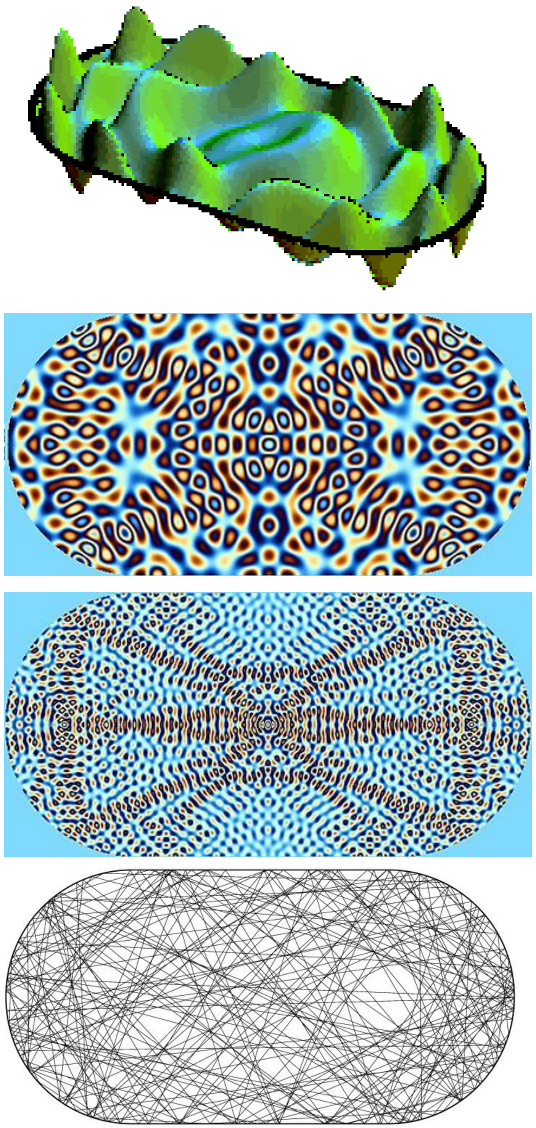
In the ray-limit it is possible to define chaos



"ray chaos"

Wave Chaos concerns solutions of linear wave equations which, in the semiclassical limit, can be described by chaotic ray trajectories

From Classical to Wave Chaos



wave

Quantum

Semiclassical limit

(quantum chaos)

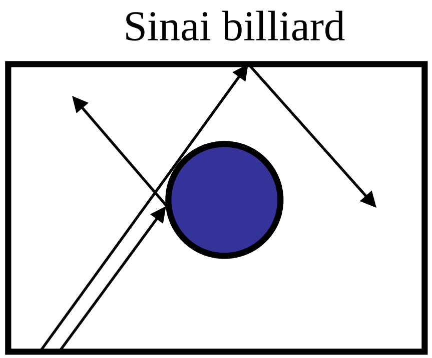
ray
trajectory

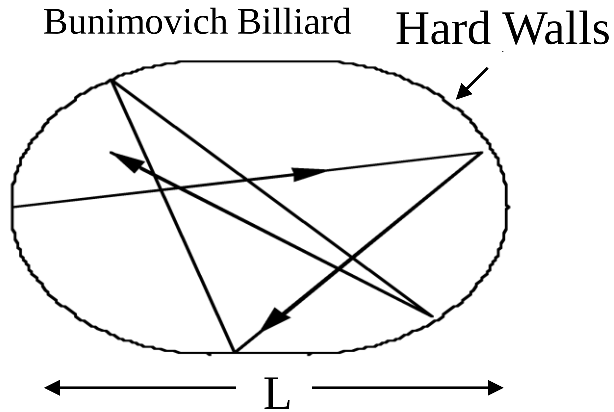
Classical

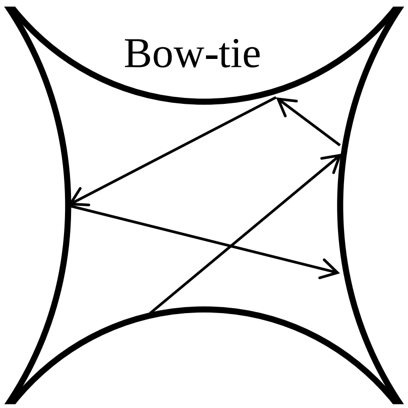
(chaos)

How Common is Wave Chaos?

Consider an infinite square-well potential (i.e. a billiard) that shows chaos in the classical limit:







Solve the wave equation in the same potential well

Examine the solutions in the semiclassical regime: $0 < \lambda << L$

Some example physical systems:
Nuclei, 2D electron gas billiards, acoustic waves in irregular blocks or rooms, electromagnetic waves in enclosures

Will the chaos present in the classical limit have an affect on the wave properties?

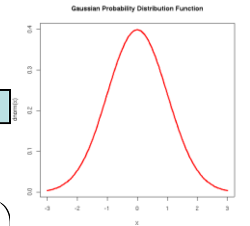
YES But how?

Random Matrix Theory (RMT)

Wigner; Dyson; Mehta; Bohigas …

The RMT Approach:

Complicated Hamiltonian: e.g. Nucleus: Solve $H\Psi = E\Psi$



Replace with a Hamiltonian with matrix elements chosen randomly from a Gaussian distribution

Examine the <u>statistical</u> properties of the resulting Hamiltonians

$$H = \begin{pmatrix} - & - & - & - & \\ - & - & - & - & \\ - & - & - & - & \cdots \\ - & - & - & - & \\ & & \vdots & & \end{pmatrix}$$

Universality Classes of RMT:
- Orthogonal (real matrix elements, β = 1)
- Unitary (complex matrix elements, β = 2)
- Symplectic (quaternion matrix elements, β = 4)

<u>Hypothesis</u>: Complicated Quantum/Wave systems that have chaotic classical/ray counterparts possess universal statistical properties described by Random Matrix Theory (RMT) "BGS Conjecture"

Cassati, 1980
Bohigas, 1984

This hypothesis has been tested in many systems:
Nuclei, atoms, molecules, quantum dots, acoustics (room, solid body, seismic), optical resonators, random lasers,…

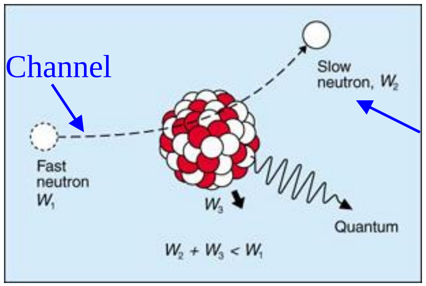
Some Questions to Investigate:
Is this hypothesis supported by data in other systems?
What new applications are enabled by wave chaos?
Can losses / decoherence be included?
What causes deviations from RMT predictions?

Chaos and Scattering

Hypothesis: Random Matrix Theory quantitatively describes the statistical properties of all wave chaotic systems (closed and **open**)

Nuclear scattering:
Ericson fluctuations

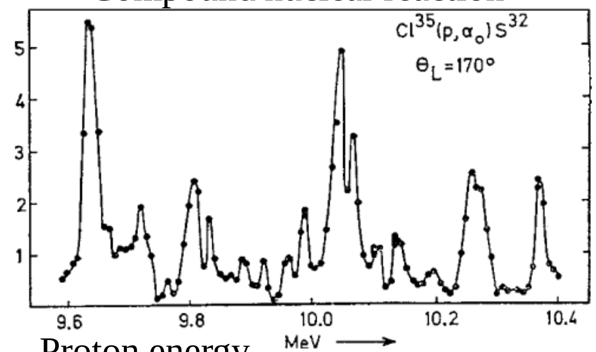
Incoming Channel



Outgoing Channel

Compound nuclear reaction

$$\frac{d\sigma}{d\omega}$$

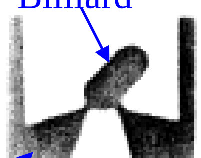


Proton energy

Transport in 2D quantum dots:
Universal Conductance Fluctuations

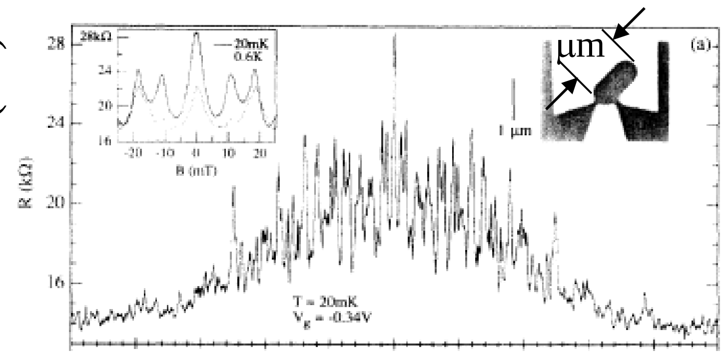
Billiard

Incoming Channel



Outgoing Channel

Resistance (kΩ)



B (T)

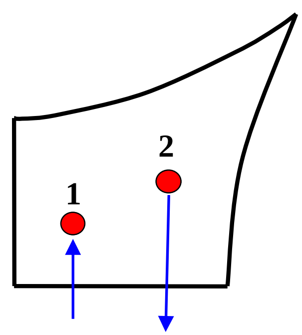
Outgoing Voltage waves

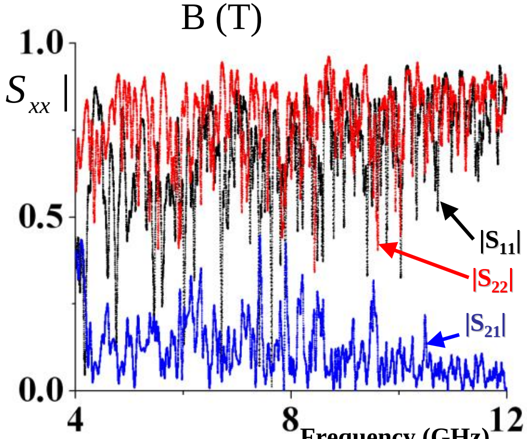
S matrix

$$\begin{bmatrix} V^-_1 \\ V^-_2 \\ \bullet \\ \bullet \\ \bullet \\ V^-_N \end{bmatrix} = [S] \cdot \begin{bmatrix} V^+_1 \\ V^+_2 \\ \bullet \\ \bullet \\ \bullet \\ V^+_N \end{bmatrix}$$

Incoming Voltage waves

Electromagnetic Cavities:
Complicated S_{11}, S_{22}, S_{21}
versus frequency





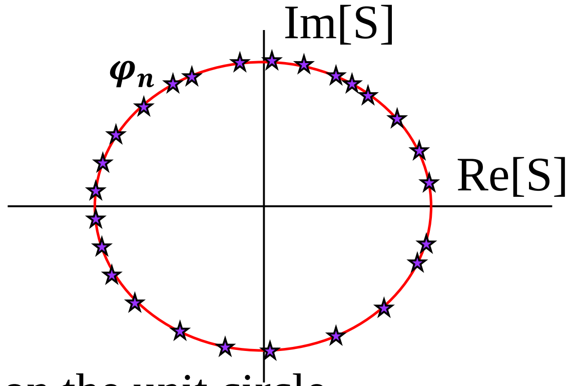
Universal Scattering Statistics

Despite the very different physical circumstances, these measured scattering fluctuations have a common underlying origin!

Universal Properties of the Scattering Matrix:

$$S = |S| e^{i\varphi}$$

Unitary Case



RMT prediction: Eigenphases of S uniformly distributed on the unit circle

Eigenphase repulsion

$$P(\varphi_1, \varphi_2, \ldots \varphi_N) \sim \prod_{n>m} \left| e^{i\varphi_n} - e^{i\varphi_m} \right|^{\beta}$$

$$\beta = \begin{cases} 1 & \text{GOE} \\ 2 & \text{GUE} \\ 4 & \text{GSE} \end{cases}$$

Nuclear Scattering Cross Section

$$\frac{d\sigma}{d\omega}$$

2D Electron Gas Quantum Dot Resistance

$$R(B)$$

Microwave Cavity Scattering Matrix, Impedance, Admittance, etc.

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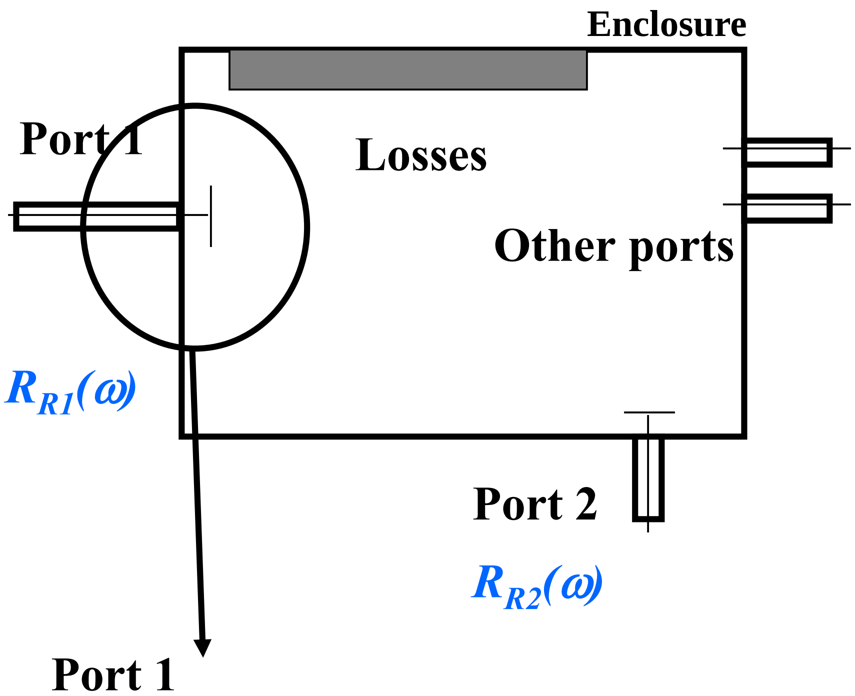
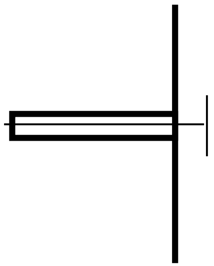
Statistical Model of Impedance (Z) Matrix

S. Hemmady, *et al.*, Phys. Rev. Lett. 94, 014102 (2005)
L. K. Warne, *et al.*, IEEE Trans. on Anten. and Prop. 51, 978 (2003)
X. Zheng, *et al.*, Electromagnetics 26, 3 (2006); Electromagnetics 26, 37 (2006)





Free-space radiation Resistance $R_R(\omega)$

$Z_R(\omega) = R_R(\omega) + jX_R(\omega)$

Statistical Model Impedance

$$Z_{ij}(\omega) = -\frac{j}{\pi}\sum_{\text{modes } n} R_{Ri}^{1/2}(\omega_n) R_{Rj}^{1/2}(\omega_n) \frac{\Delta\omega_n^2 \, w_{in} w_{jn}}{\omega^2(1+jQ^{-1}) - \omega_n^2}$$

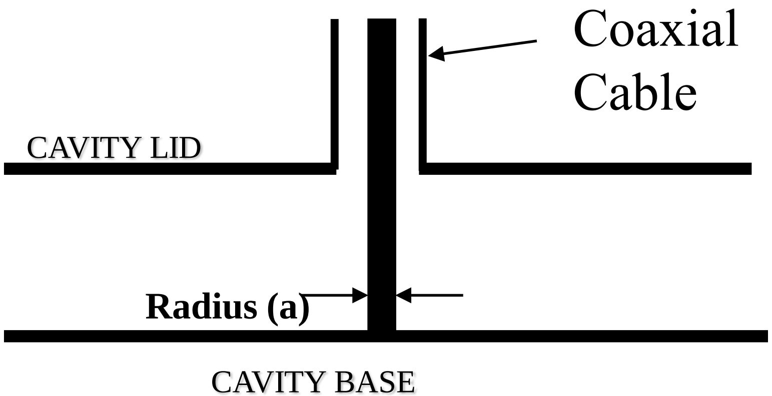
System parameters
- **Radiation Resistance $R_{Ri}(\omega)$**
- **$\Delta\omega_n^2$ - mean spectral spacing**
- **Q -quality factor**

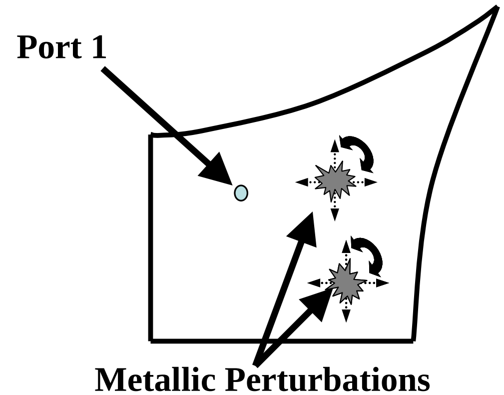
Statistical parameters
- **ω_n - random spectrum (RMT)**
- **w_{in}- Guassian Random variables**

$$\propto = \frac{\omega^2}{\Delta\omega^2 \, Q}$$

Testing Insensitivity to Sys

Cross Section View of Port

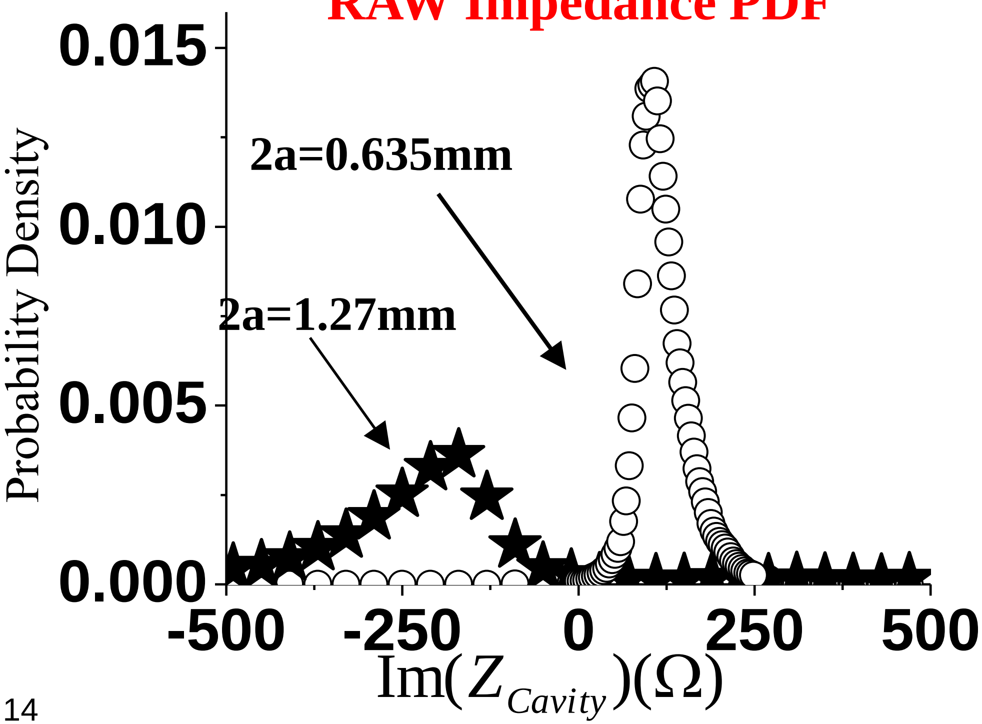




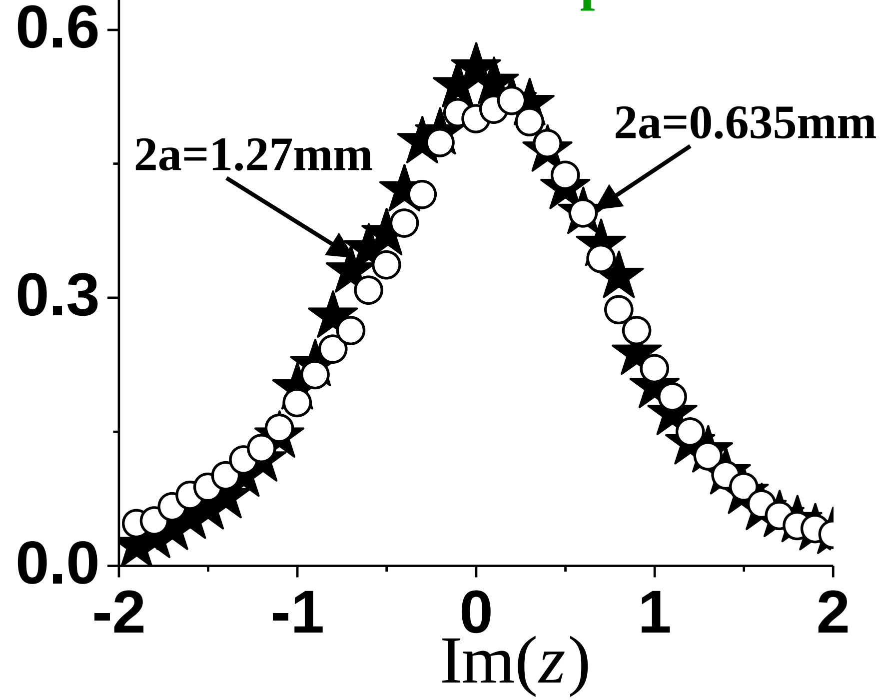
$$z = \frac{R_{Cavity}}{R_{Rad}} + i\,\frac{X_{Cavity} - X_{Rad}}{R_{Rad}}$$

$$Z_{Cavity} = iX_{Rad} + R_{Rad}\, z$$

RAW Impedance PDF



NORMALIZED Impedance PDF

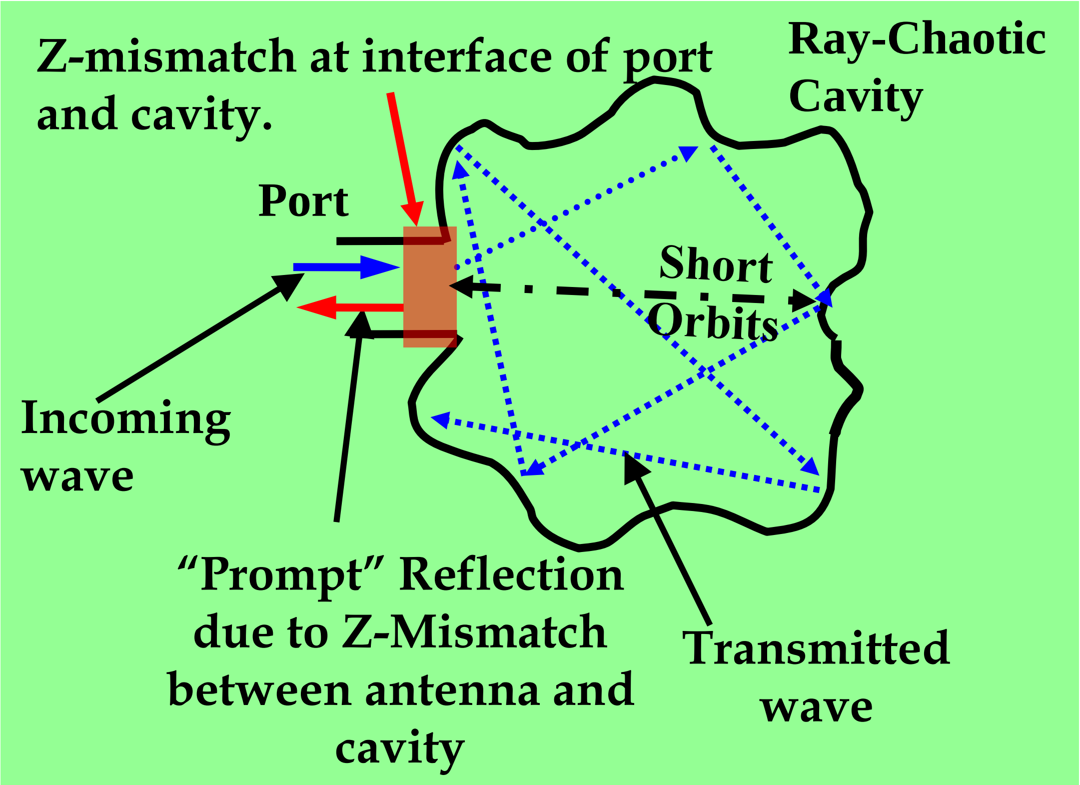


Universal Fluctuations are Usually Obscured by Non-Universal System-Specific Details

Wave-Chaotic systems are sensitive to details

The Most Common Non-Universal Effects:

1) Non-Ideal Coupling between external scattering states and internal modes (i.e. Antenna properties)
2) Short-Orbits between the antenna and fixed walls of the billiards



The Random Coupling Model

http://anlage.umd.edu/RCM

Divide and Conquer!

Coupling Problem

Solution: Radiation Impedance Matrix $\mathbf{Z}_{rad}$ + Short Orbits

Enclosure Problem

Solution: Random Matrix Theory; Electromagnetic statistical properties are governed by Loss Parameter $\boldsymbol{\alpha} = k^2/(\Delta k_n^2\, Q) = \delta f_{3dB}/\Delta f_{spacing}$

$$Z = \overline{Z} + \tilde{Z} = iX_{Rad} + i\xi R_{Rad}$$

Mean part

Fluctuating Part (depends on $\boldsymbol{\alpha}$)

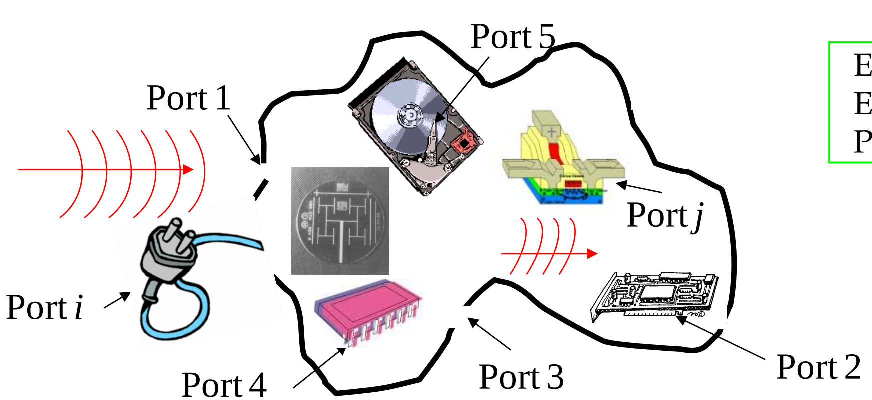
$\langle \mathrm{Im}\xi \rangle = 1$

$\langle \mathrm{Re}\xi \rangle = 0$

Z matrix

$$\begin{bmatrix} V_1 \\ V_2 \\ \bullet \\ \bullet \\ \bullet \\ V_N \end{bmatrix} = [Z] \cdot \begin{bmatrix} I_1 \\ I_2 \\ \bullet \\ \bullet \\ \bullet \\ I_N \end{bmatrix}$$

IEEE Trans. EMC 54, 758 (2012)



Electromagnetics 26, 3 (2006)
Electromagnetics 26, 37 (2006)
Phys. Rev. Lett. 94, 014102 (2005)

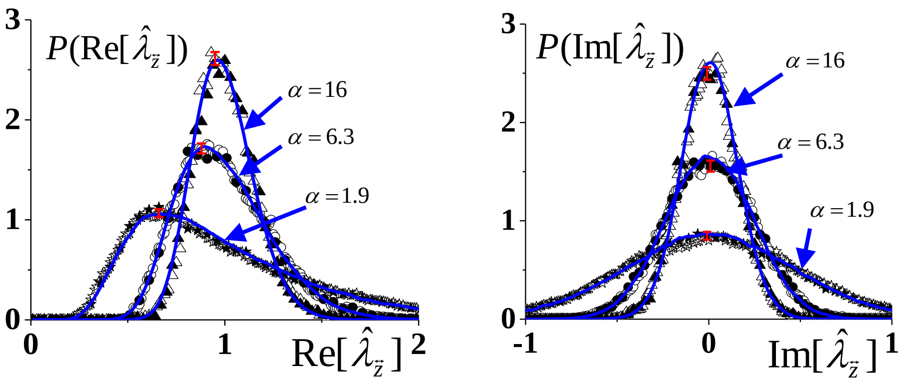
Statistical Properties of Scattering Systems

Universal Z (reaction) and S statistics

Inclusion of loss: $P_\alpha(Z)$, $P_\alpha(S)$

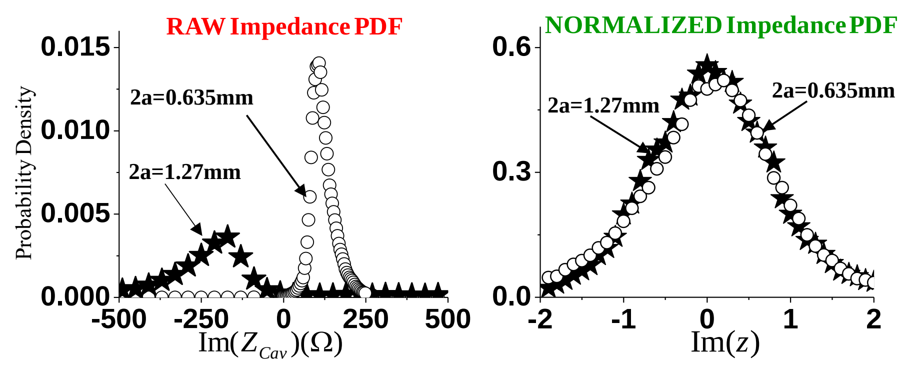
α = 3-dB bandwidth / mean-spacing

Phys. Rev. Lett. **94**, 014102 (2005)
Phys. Rev. E **74**, 036213 (2006)



Removing Non-Universal Effects:
Sensitivity to Details
Coupling, Short Orbits

Phys. Rev. E **80**, 041109 (2009)
Phys. Rev. E **81**, 025201(R) (2010)



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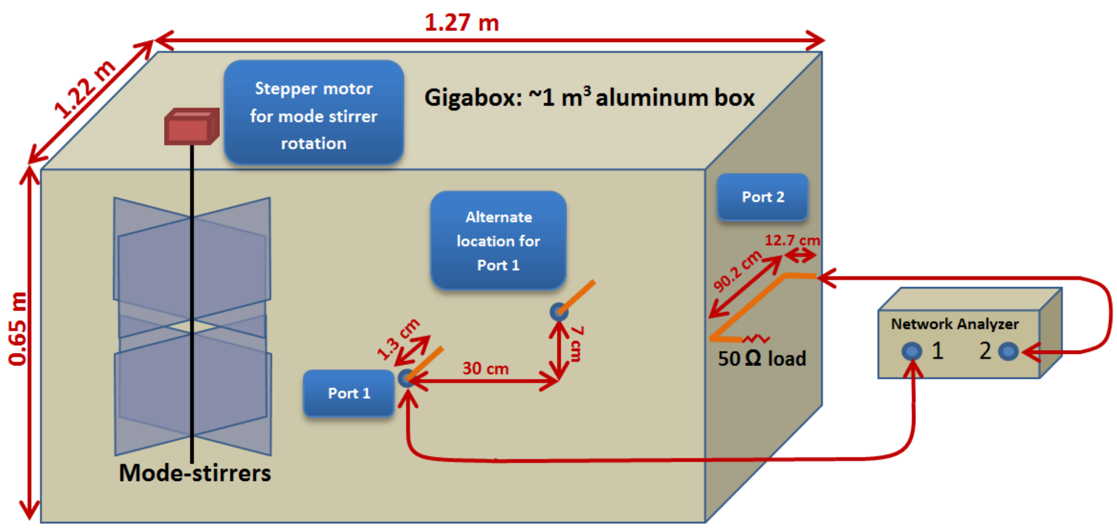
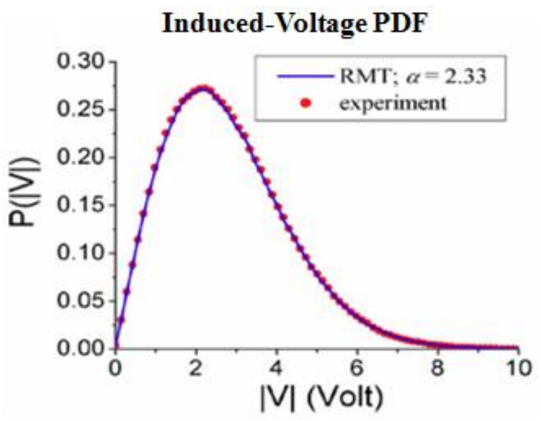
Test of the Random Coupling Model: Gigabox Experiment
(NRL Collaboration)





1. Inject microwaves at port 1 and measure induced voltage at port 2
2. Rotate mode-stirrer and repeat
3. Plot the PDF of the induced voltage and compare with RCM prediction

But this is at the limit of what we can test in our labs …

Z. B. Drikas, *et al*., IEEE EMC 56, 1480 (2014)
J. Gil Gil, *et al*., IEEE EMC 58, 1535 (2016)
US Naval Research Laboratory collaboration

Extensions to the Original Random Coupling Model

Extension	Investigated Experimentally?
Short Orbits	Yes (Z_{avg}, Fading, Time-reversal)
Multiple Coupled Enclosures	In progress
Nonlinear Systems	Yes (First results on billiard with nonlinear active circuit)
Coupling Through Apertures	Yes (Analyzing data)
Mixed (regular + chaotic) systems	In progress
Lossy Ports	Yes (Radiation efficiency correction η)
Integration with FEM codes	

… and making connections to:

Power Balance / SEA / DEA / Correlation Fcns. (U. Nottingham)
Reverberation Chamber studies (NIST/Boulder)
Electromagnetic Topology / BLT (U. New Mexico, ONERA)

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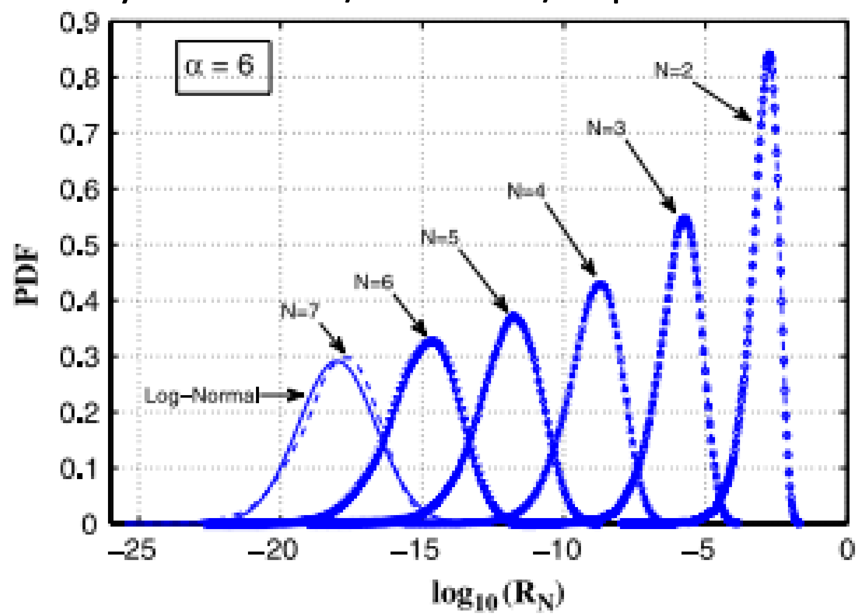
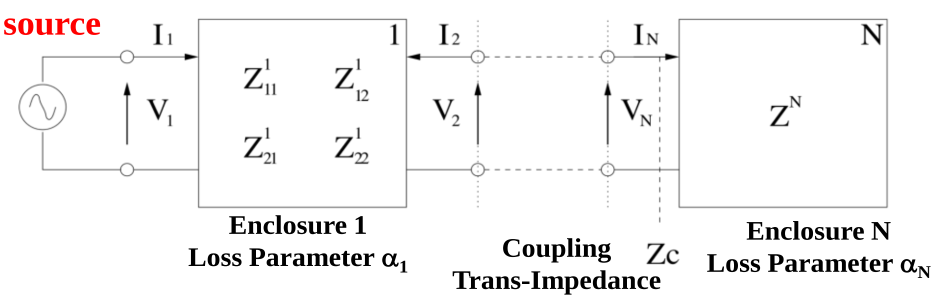
Coupled Lossy Cavities

- RCM predicts the transmission through N cavities coupled through apertures
- Experiment requires a chain of Gigaboxes

Ability to predict coupled voltage and power along an arbitrary chain of ray-chaotic cavities/environments/compartments





G. Gradoni, T. M. Antonsen, and E. Ott, Phys. Rev. E **86**, 046204 (2012).

Scaling Properties of Maxwell's Equations for Harmonic EM waves

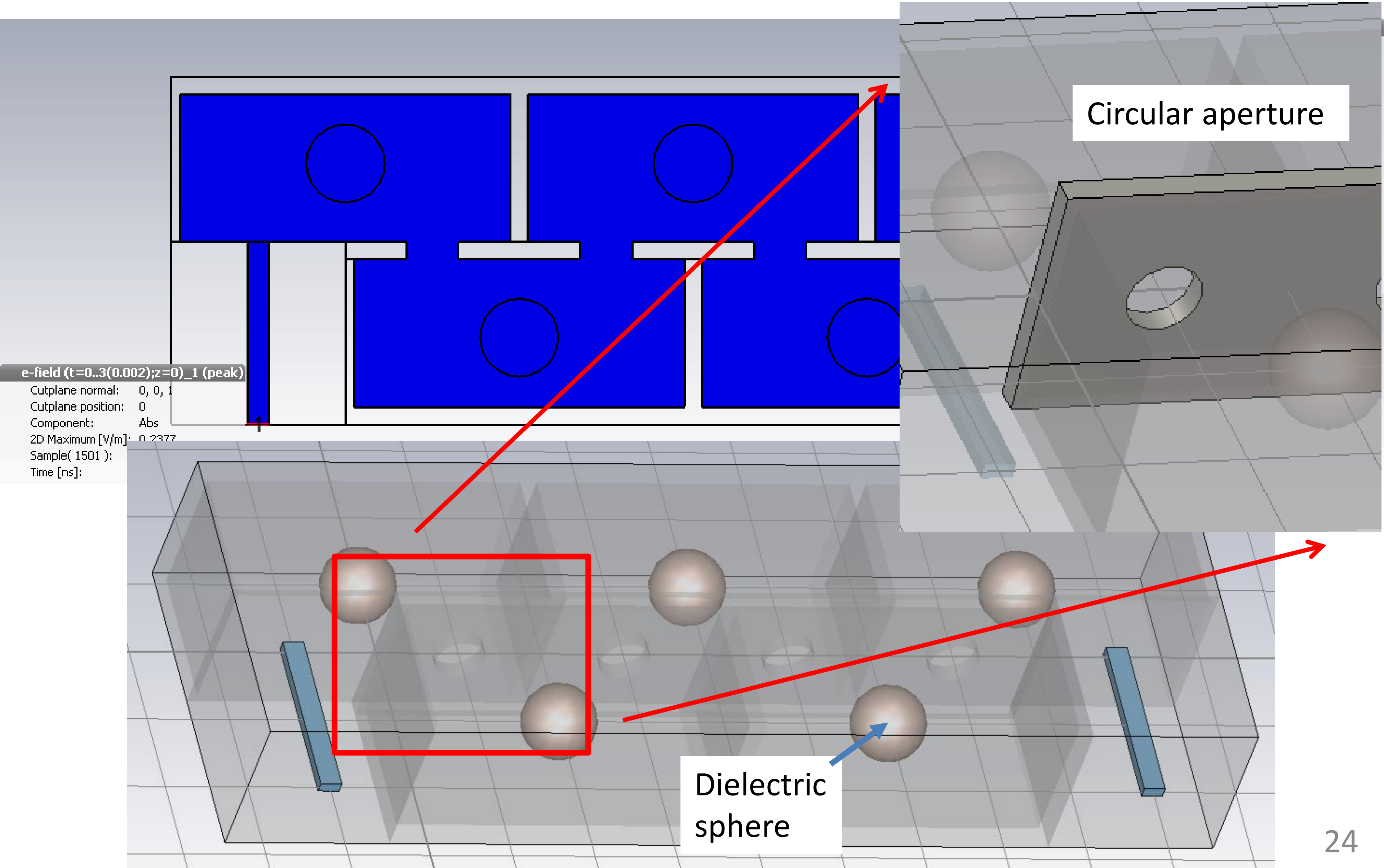
Maxwell's equations are left invariant upon scaling:

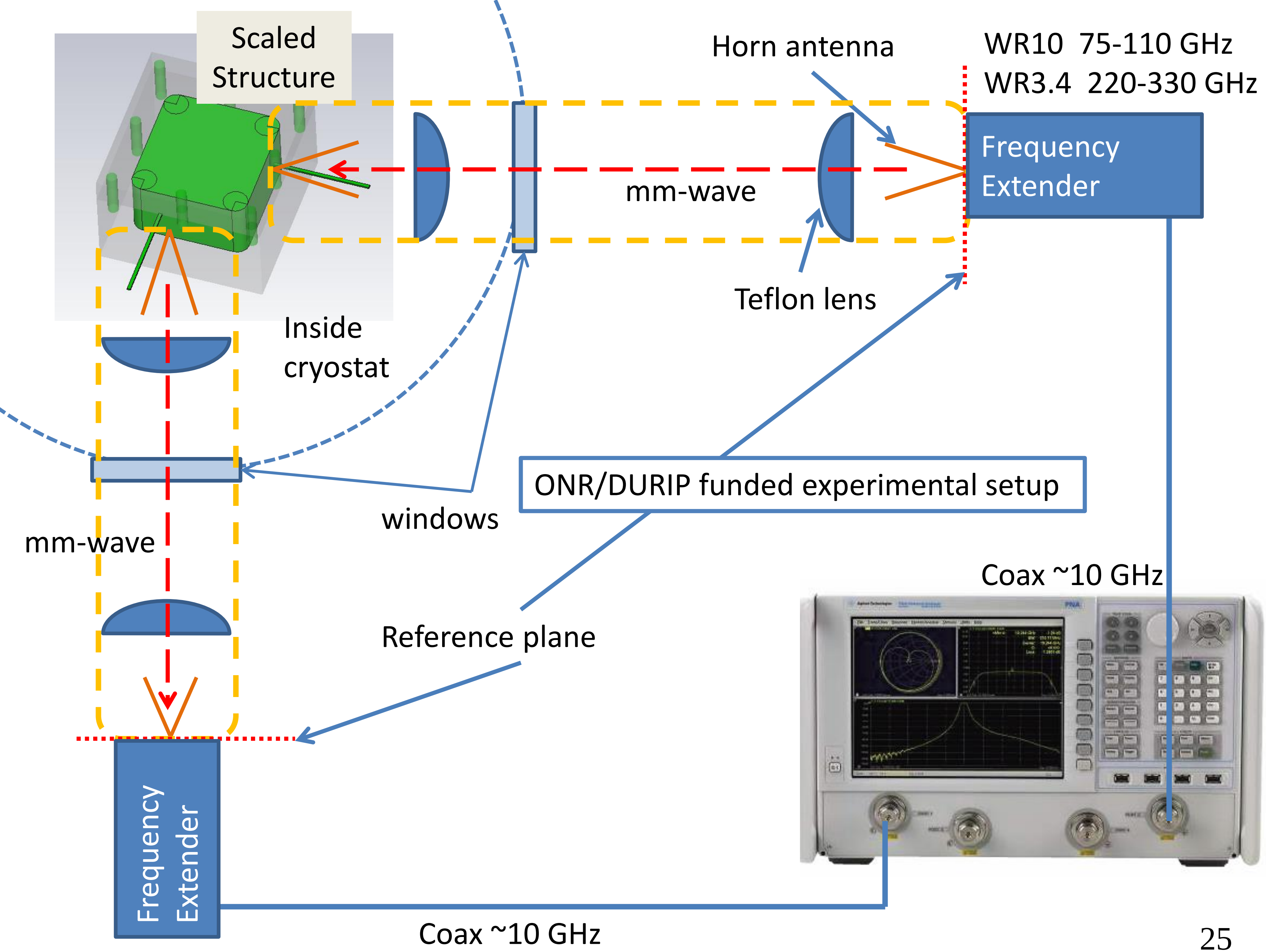
$$\vec{r}' = \frac{\vec{r}}{s} \qquad \omega' = s\omega \qquad \sigma' = s\sigma$$

For example, scaling the GigaBox down by a factor of ***s*** = 20 requires:

1 m x 1 m x 1 m Box	→	5 cm x 5 cm x 5 cm Box
5 GHz measurement	→	100 GHz measurement
Wall conductivity σ	→	Wall conductivity ***s****σ

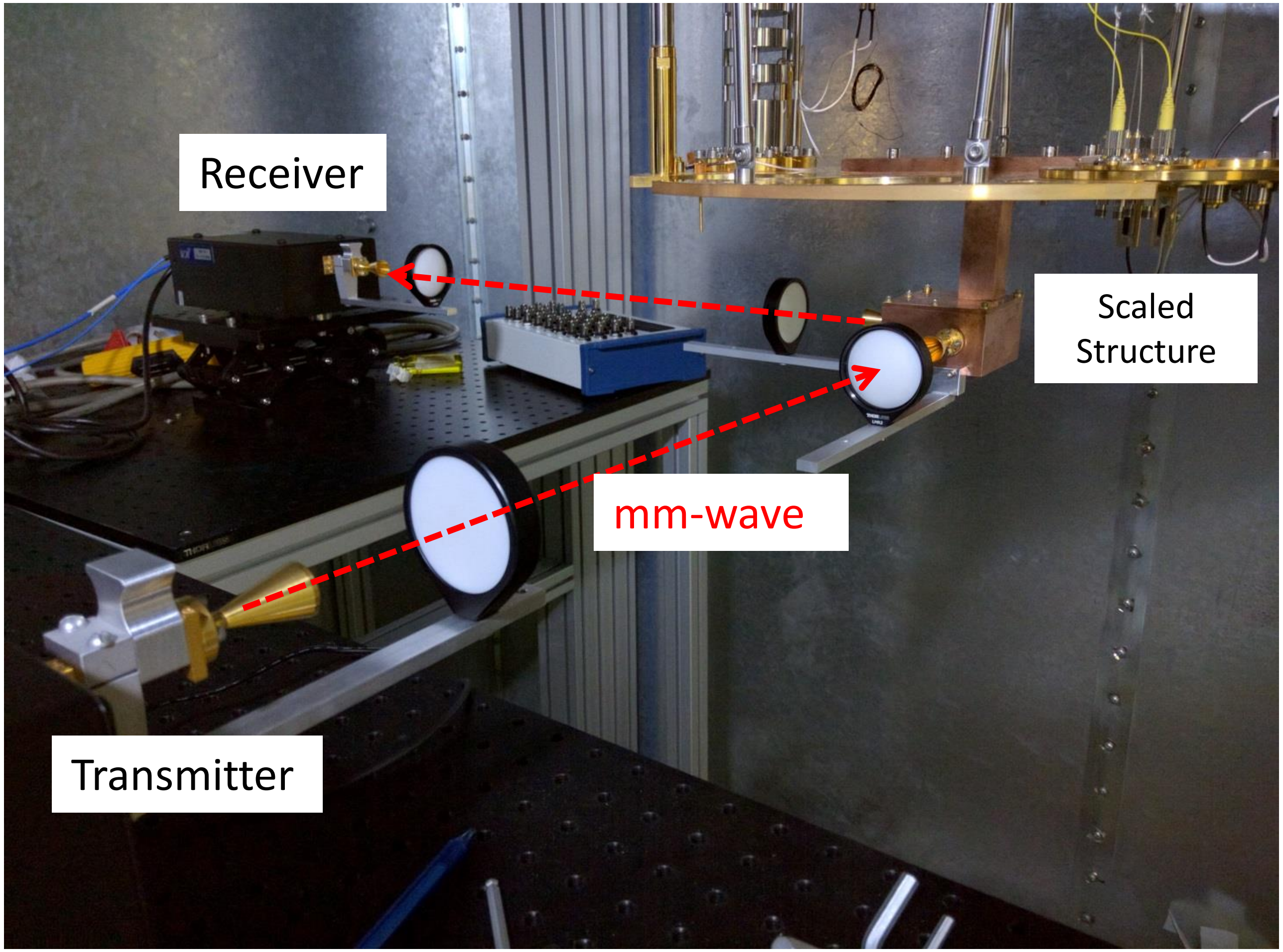
Scaled Coupled Cavities Simulation





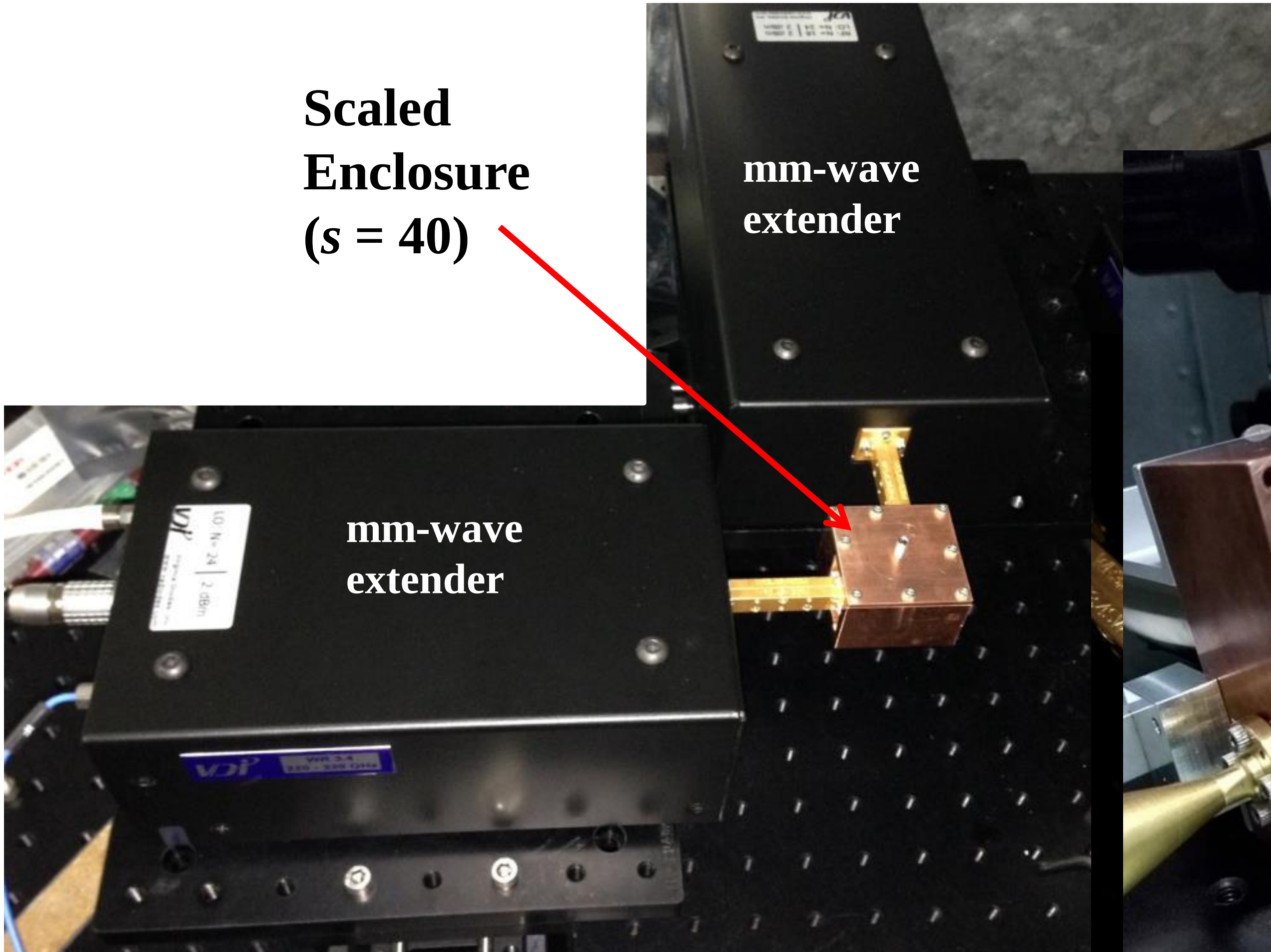
Scaled Structure
Horn antenna
WR10 75-110 GHz
WR3.4 220-330 GHz
Frequency Extender
mm-wave
Teflon lens
Inside cryostat
windows
ONR/DURIP funded experimental setup
mm-wave
Coax ~10 GHz
Reference plane
Frequency Extender
Coax ~10 GHz

Experimental Setup

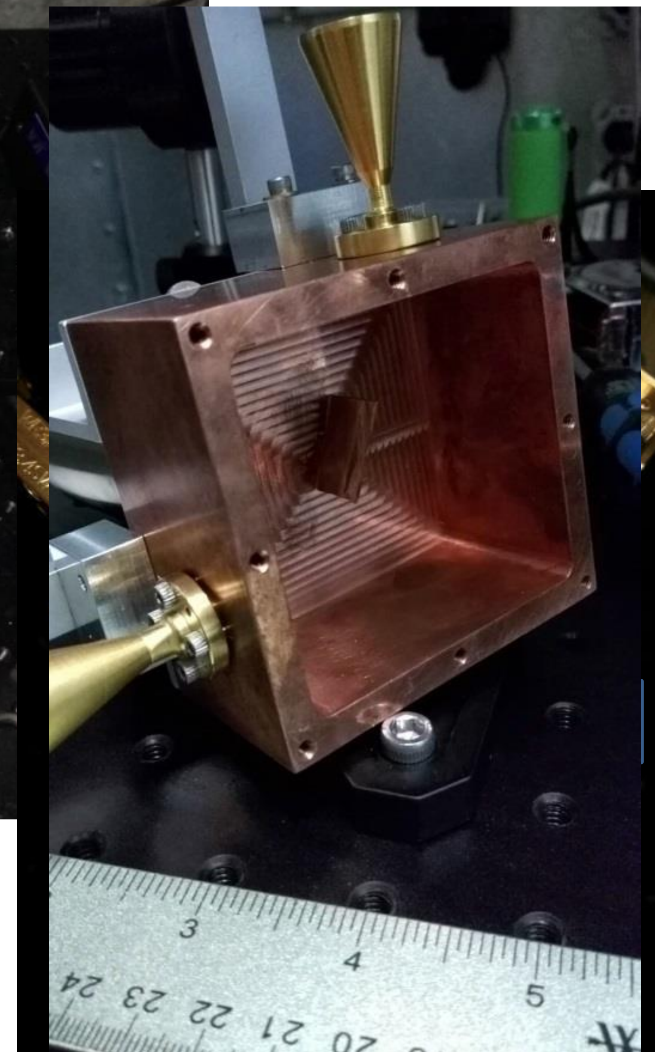


Scaled Enclosure Direct Injection Measurement

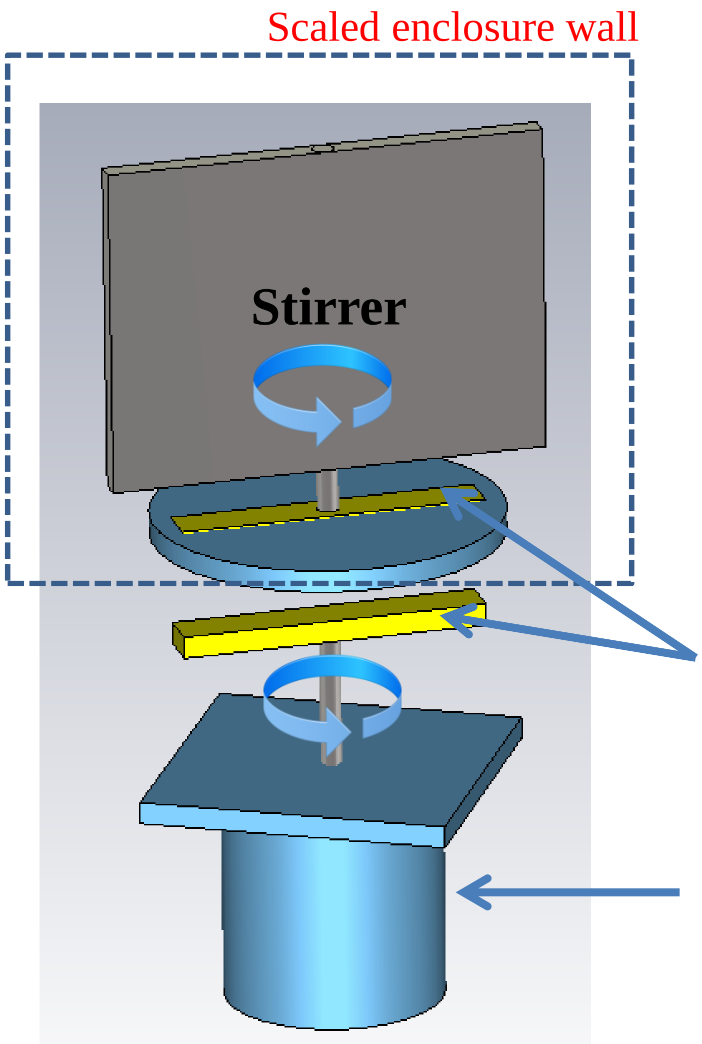
Scaled Enclosure (*s* = 40)



Scaled Enclosure (*s* = 20) with rotating perturber



Cryogenic Mode Stirrer



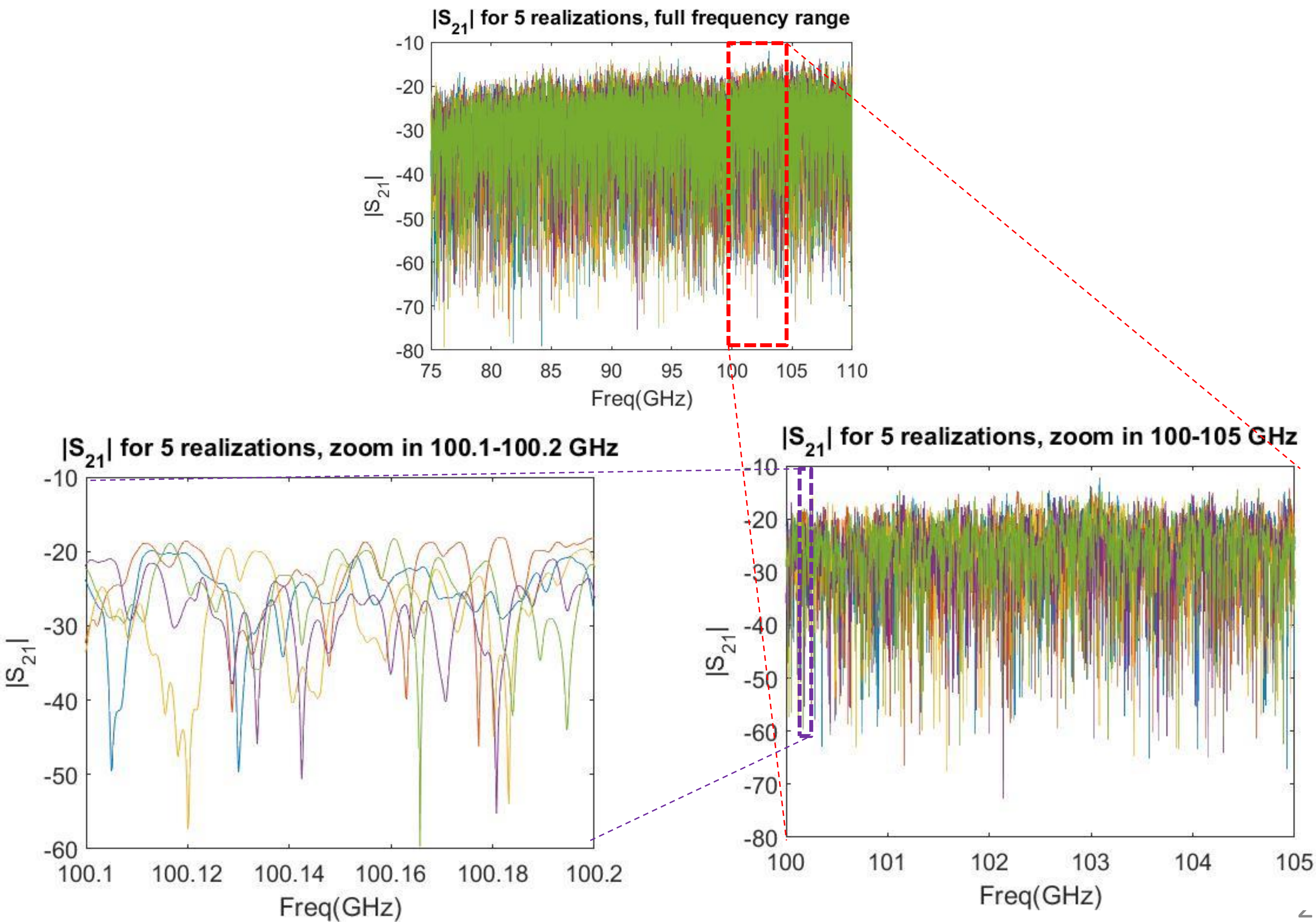
Use cryogenic stepper motor to rotate a magnetic strip below scaled cavity, causing the stirrer panel inside cavity to rotate.

No holes in the cavity walls (no leakage)

Bar Magnet

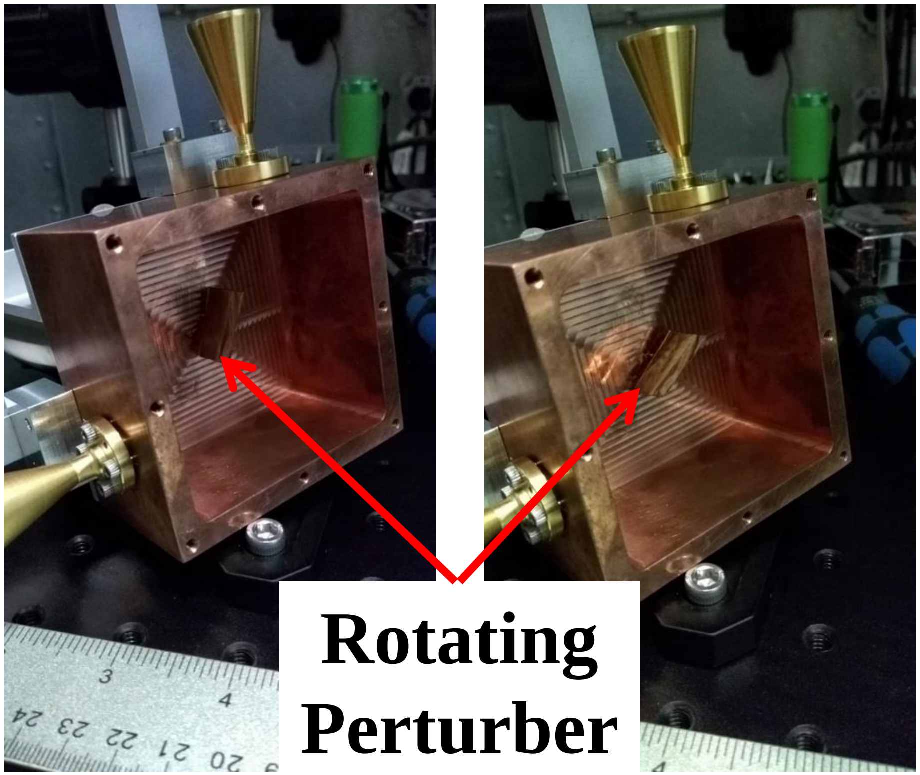
Cryogenic stepper motor

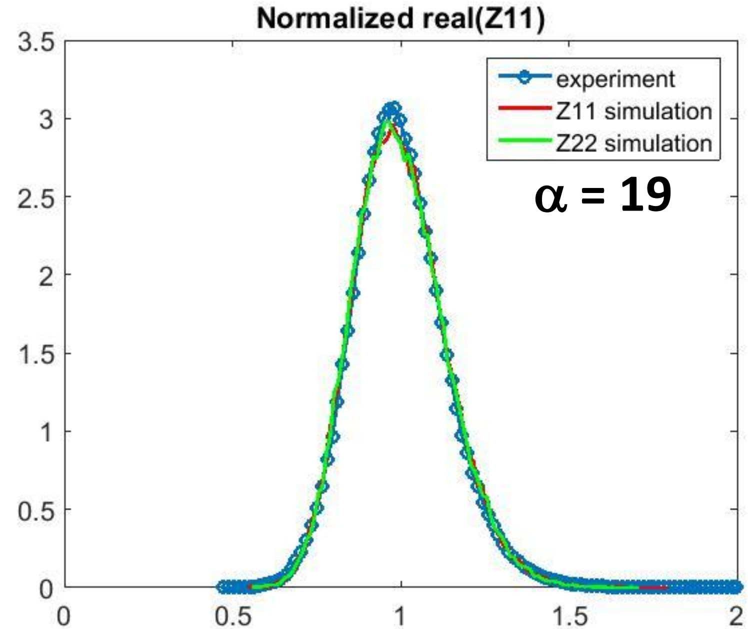
Multiple Realizations of s = 20 Scaled Enclosure at Cryogenic Temperatures

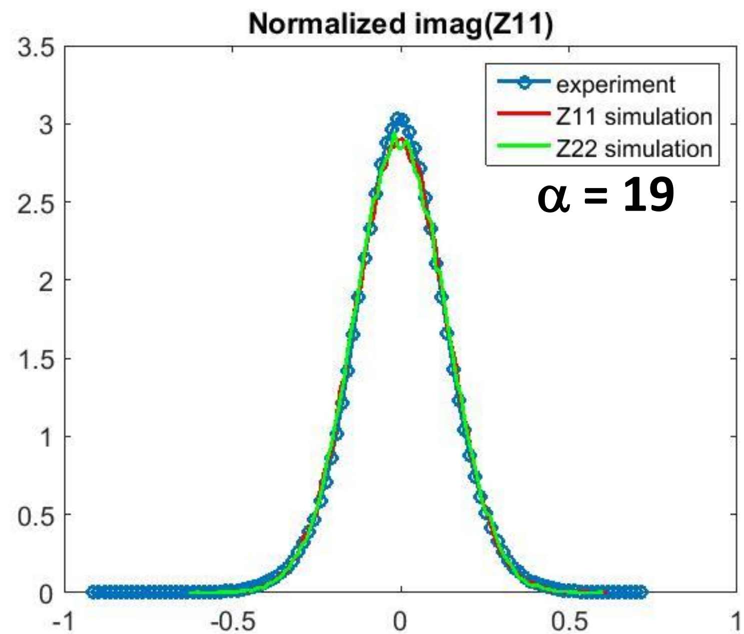


Cryogenic Results for the s = 20 Scaled Enclosure

Motion of the Perturber (Cu Sheet) Inside the s = 20 Scaled Enclosure



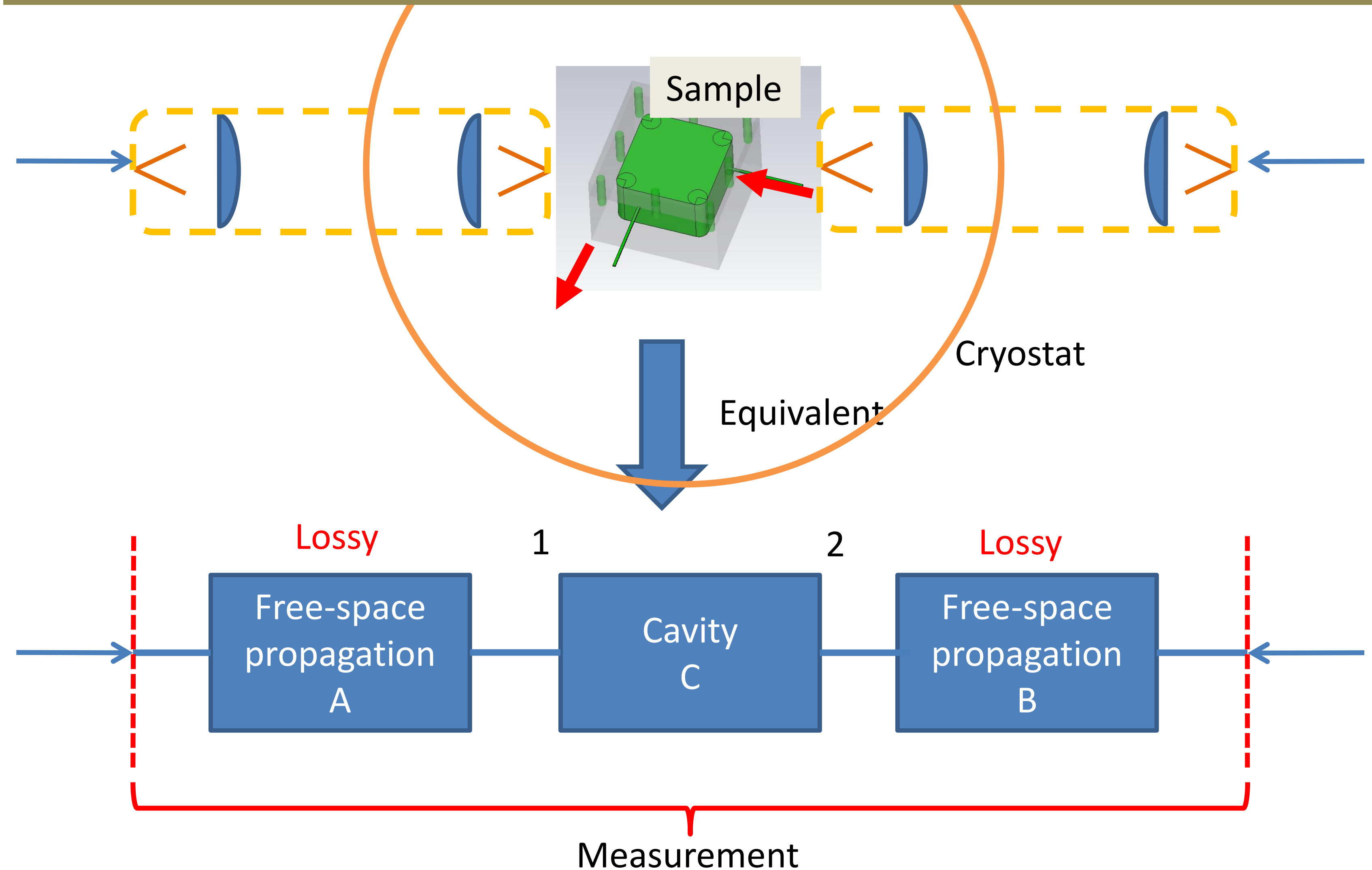




Statistics with just 9 Realizations 75 – 110 GHz

Problem: The “ports” are lossy

The original RCM assumed loss-less ports



Ports A & B will influence RCM obtained α since they are lossy

Solution: Include the Radiation Efficiency of the Ports

Scalar Form

$Z_{cav} = j\text{Im}[Z_{rad}] + \text{Re}[Z_{rad}]\xi$

Lossy antenna →

$Z_{cav} = Z_{ant} + \eta\text{Re}[Z_{ant}](\xi - 1)$

Radiation efficiency (arrow pointing to η)

Matrix Form

$Z_{cav} = j\text{Im}[Z_{rad}] + \text{Re}[Z_{rad}]^{1/2}\xi\ \text{Re}[Z_{rad}]^{1/2}$

Lossless port: $\eta = I$

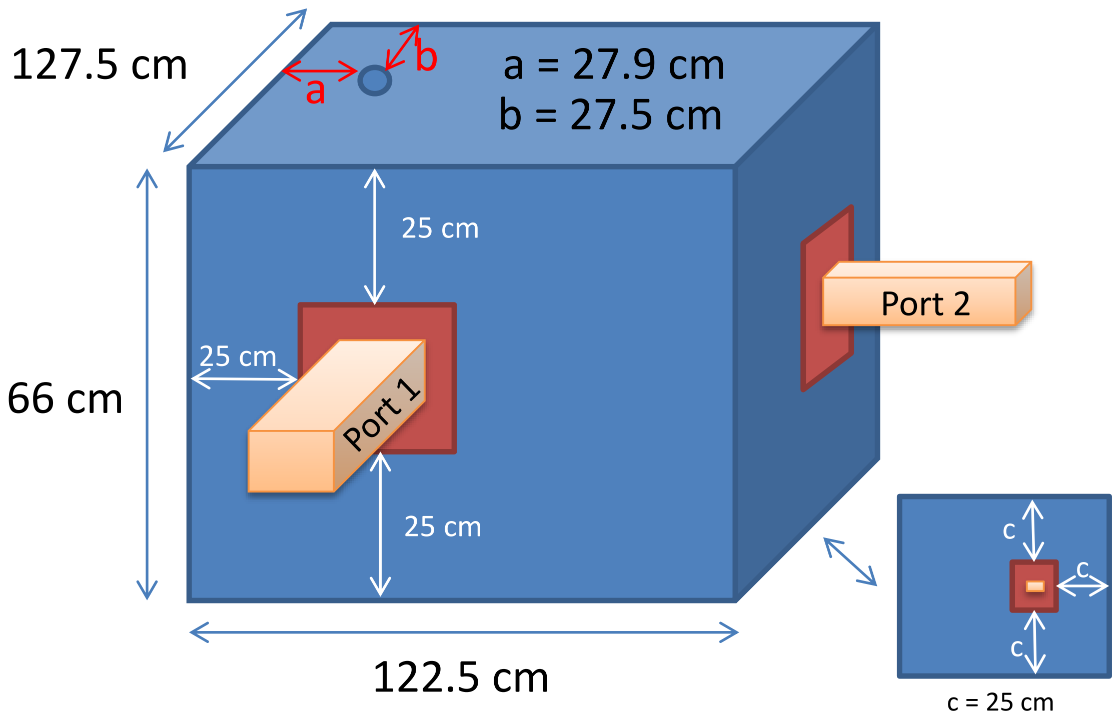
Lossy path →

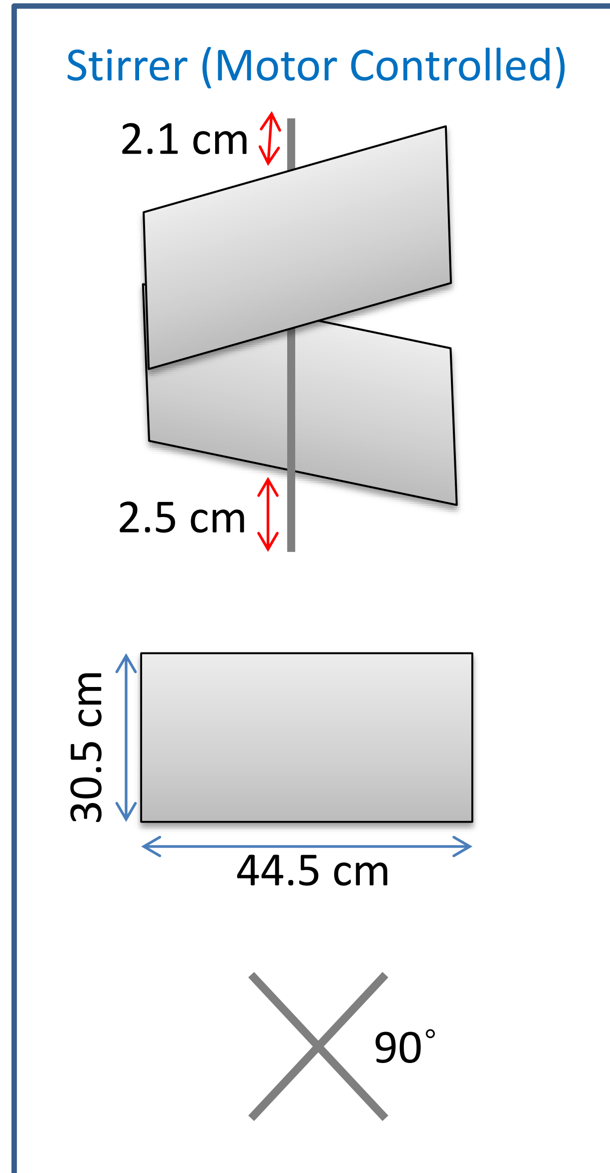
$Z_{cav} = Z_{ant} + R^{1/2}(\xi - I)R^{1/2}$

$R = \eta^{1/2}\text{Re}[Z_{ant}]\eta^{1/2}$

B. D. Addissie, J. C. Rodgers and T. M. Antonsen, "Application of the random coupling model to lossy ports in complex enclosures," *Metrology for Aerospace (MetroAeroSpace), 2015 IEEE*, Benevento, 2015, pp. 214-219.

Scaled Enclosure Measurement Validation: Compare to NRL Full-Scale Experimental Setup





We measure two scaled versions:

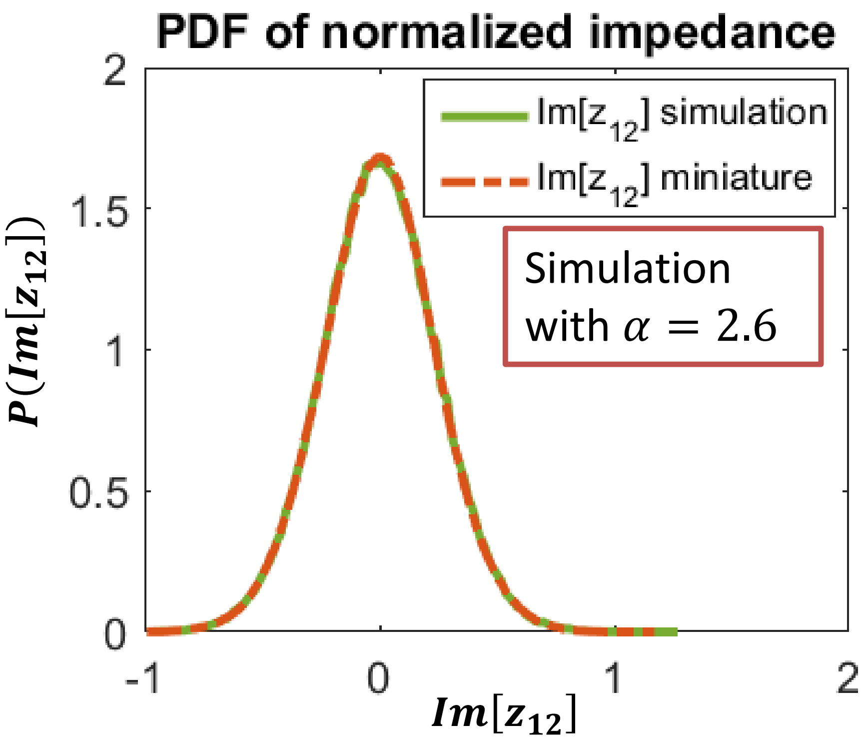
75 GHz – 110 GHz (*s* = 20) → 3.7 GHz – 5.5 GHz
WR-187 (G-Band)

220 GHz – 330 GHz (*s* = 40) → 5.5 GHz – 8.25 GHz
WR-137 (C-Band)

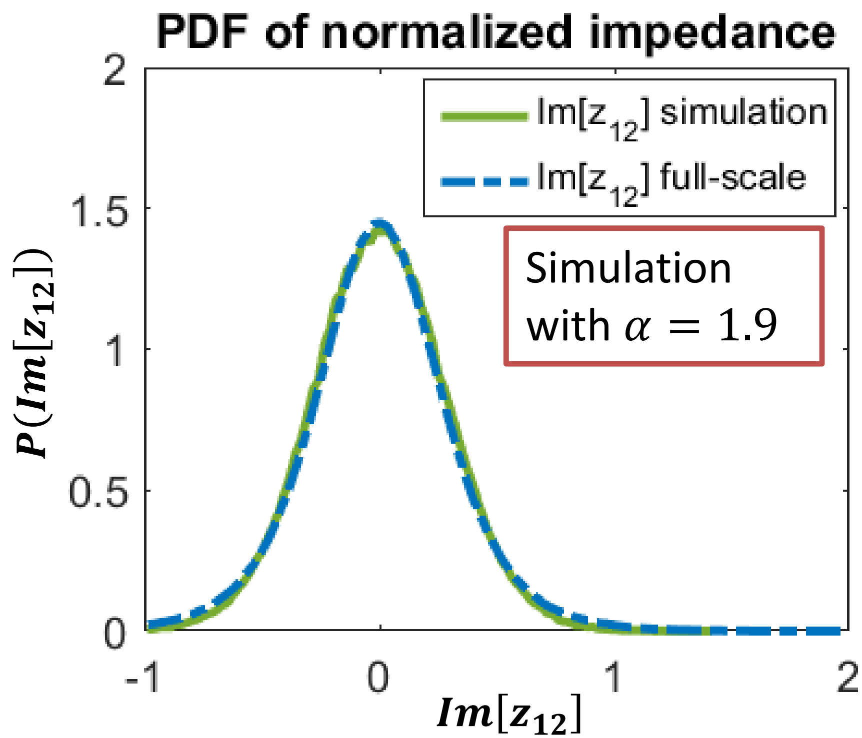
Zach Drikas, Jesus Gil Gil, T. D. Andreadis @ NRL

Single Cavity Experiment

s = 20 scaled cavity, cryogenic



Full-scale cavity, room temperature

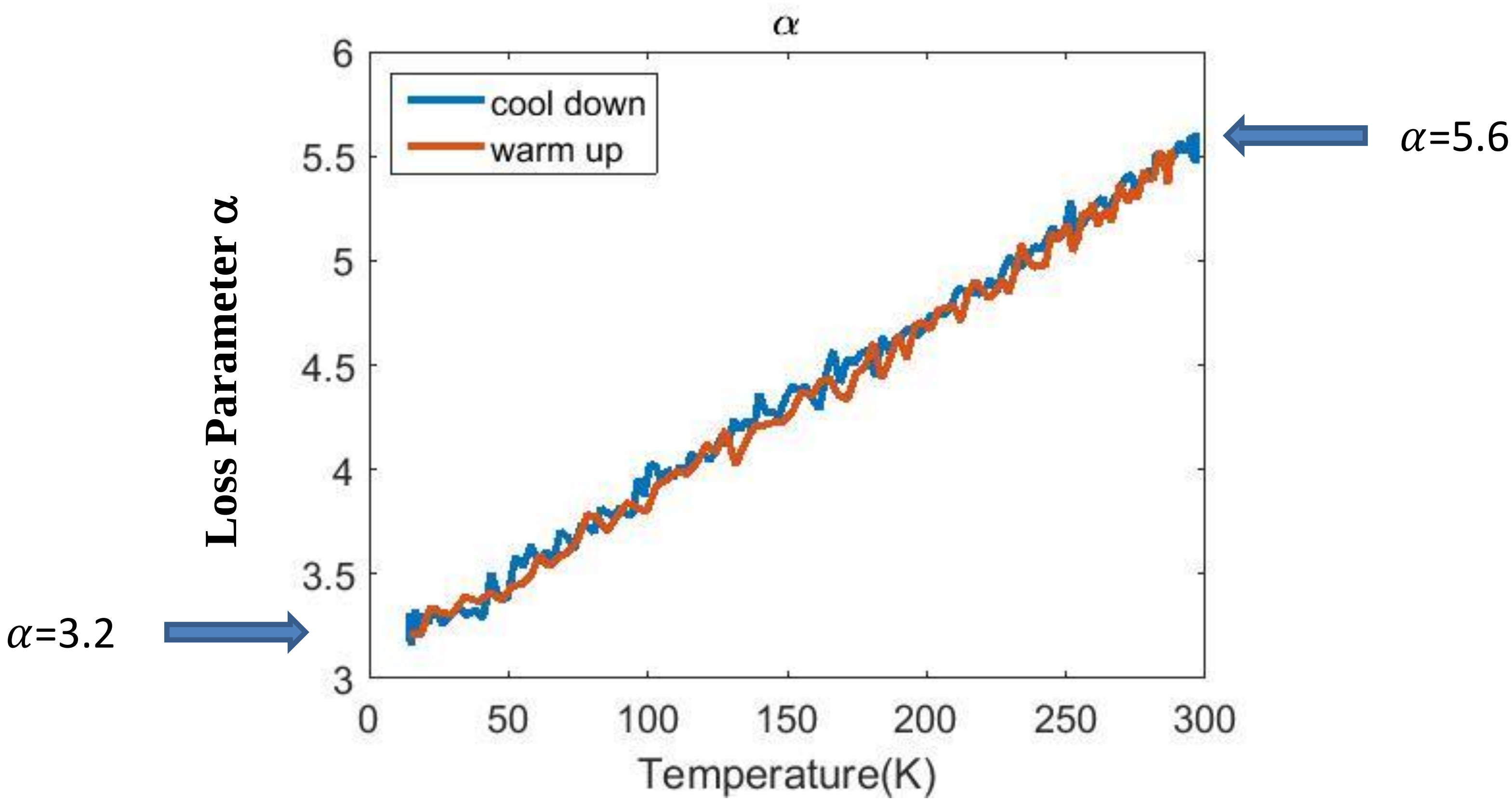


Our ongoing work is to increase full-scale cavity's α to make it within the tunable range of 2.6 – 4.2

Variation of Loss Parameter α With Temperature

s = 20 scaled cavity

$$\alpha = \frac{k^2}{Q\Delta k_n^2} = \frac{k^3 V}{2\pi^2 Q}$$



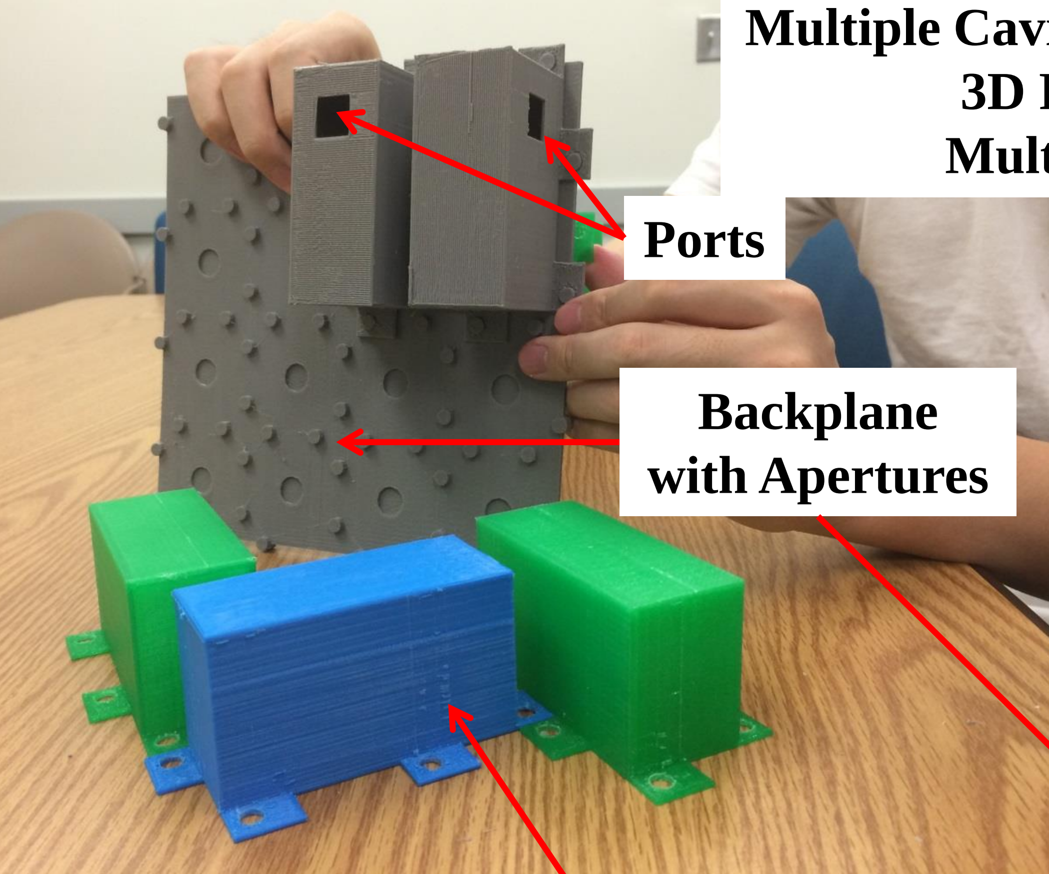
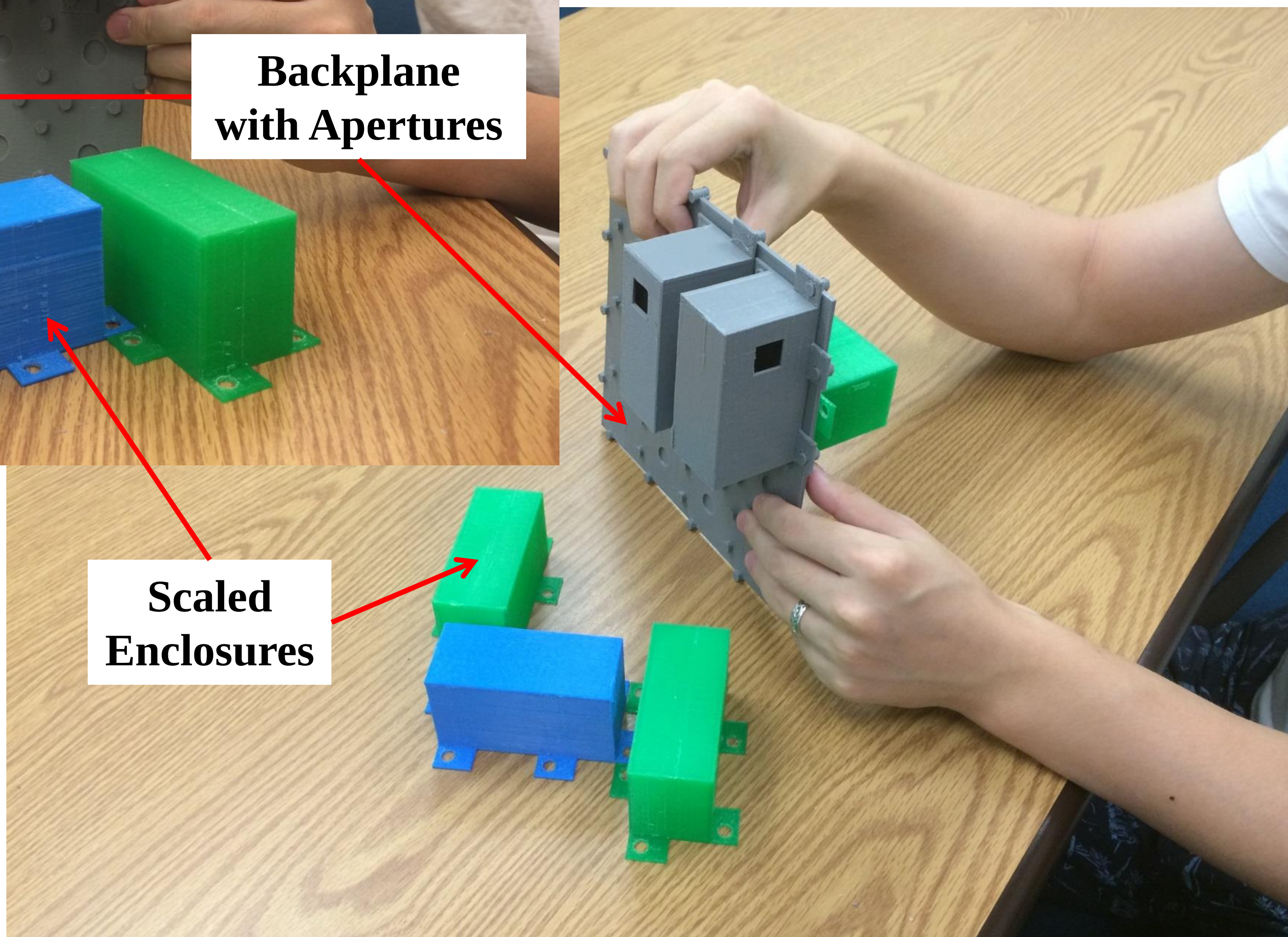
Overview of the Scaled Cavity Measurement Project

Test the Random Coupling Model in a set of increasingly complicated (and realistic) scenarios:

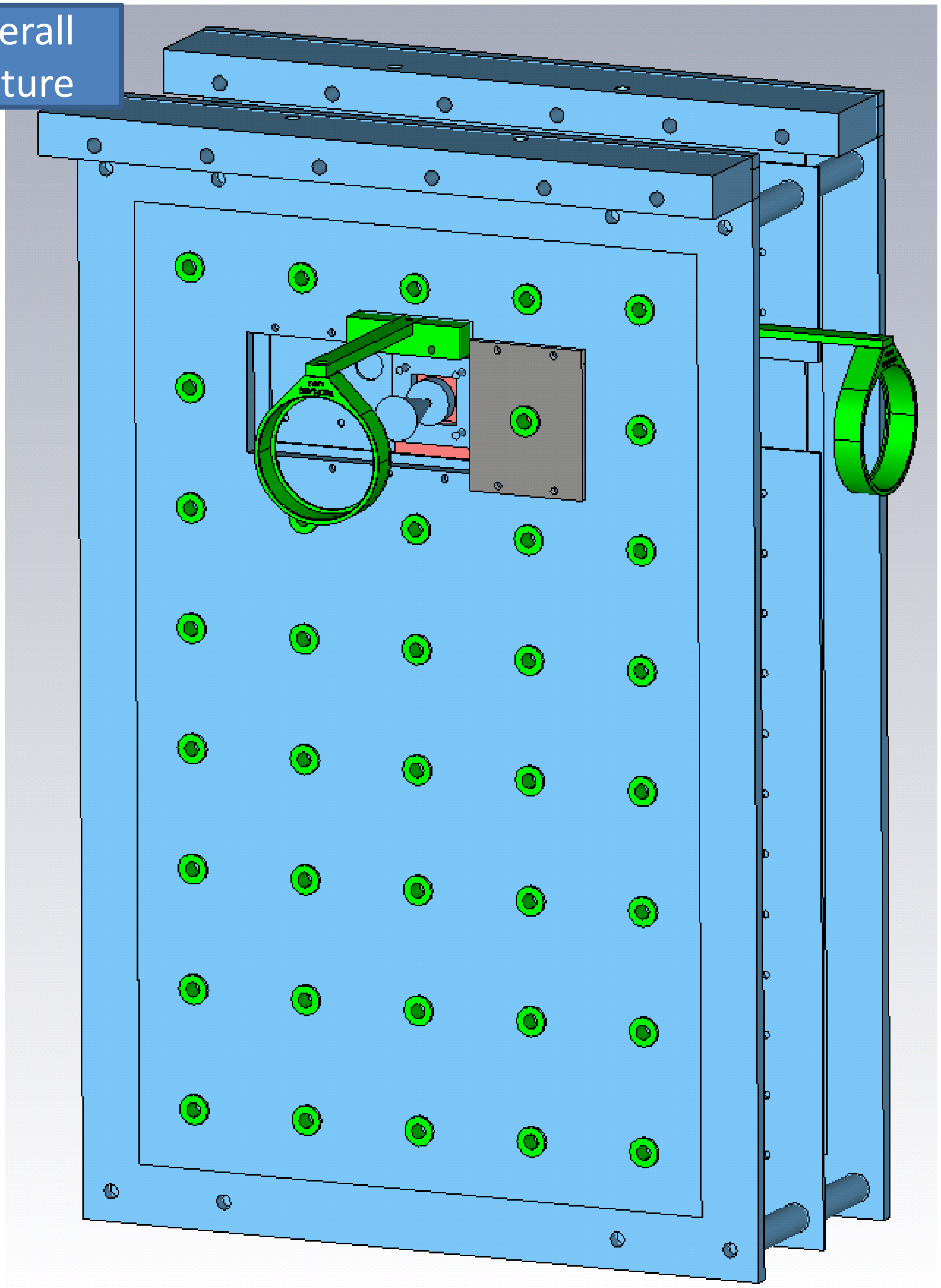
- **Multiple coupled cavities**
- **Mixed (regular + chaotic) systems**
- **Irradiation through irregular apertures**
- **Evanescent coupling between enclosures**
- **etc.**

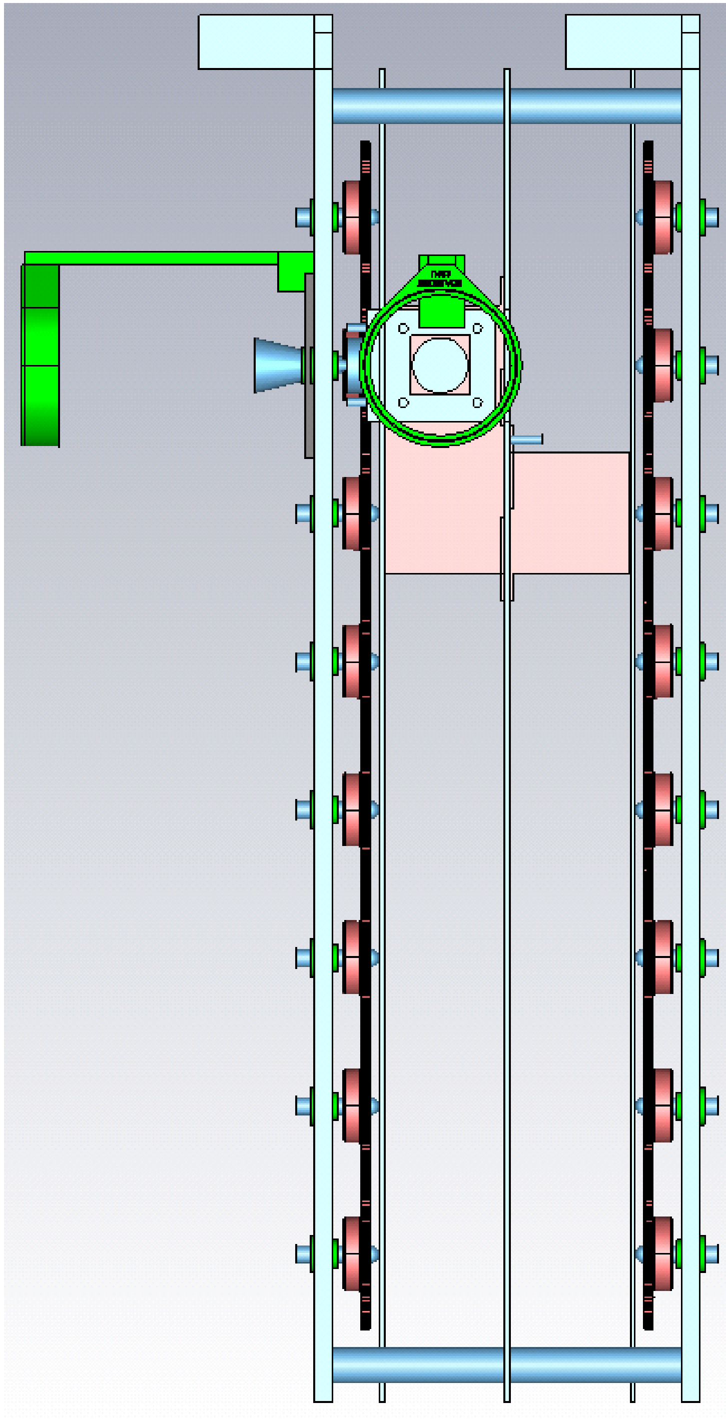
Validation step: compare to full-scale measurements at NRL

Multiple Cavity Experiment Under Development
3D Printed Scaled Structures:
Multiple Connected Enclosures

Overall picture



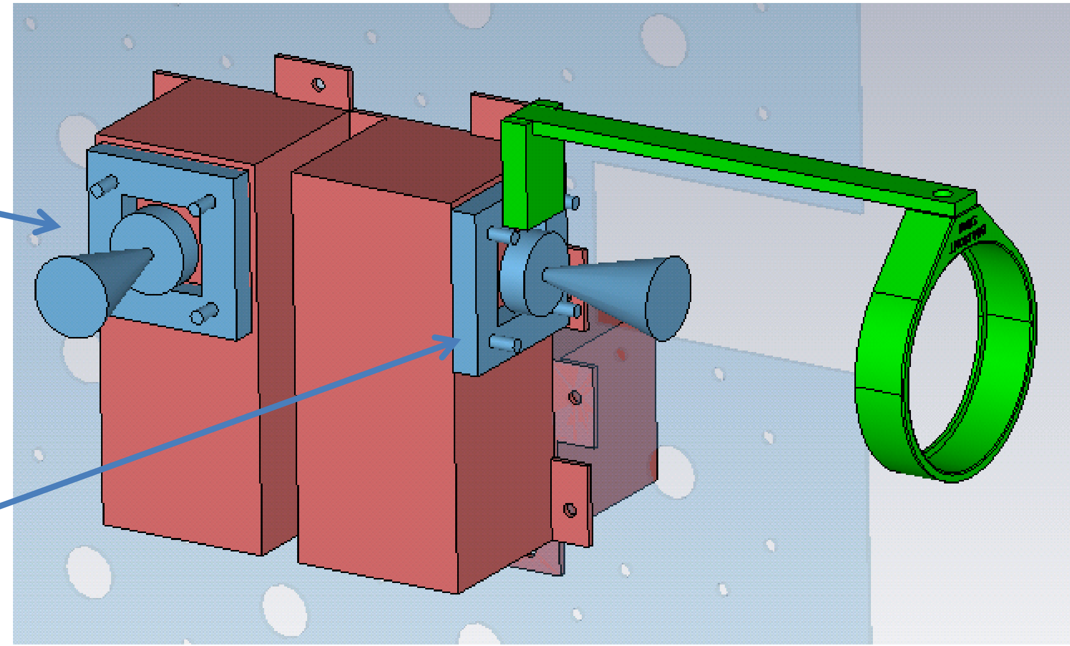


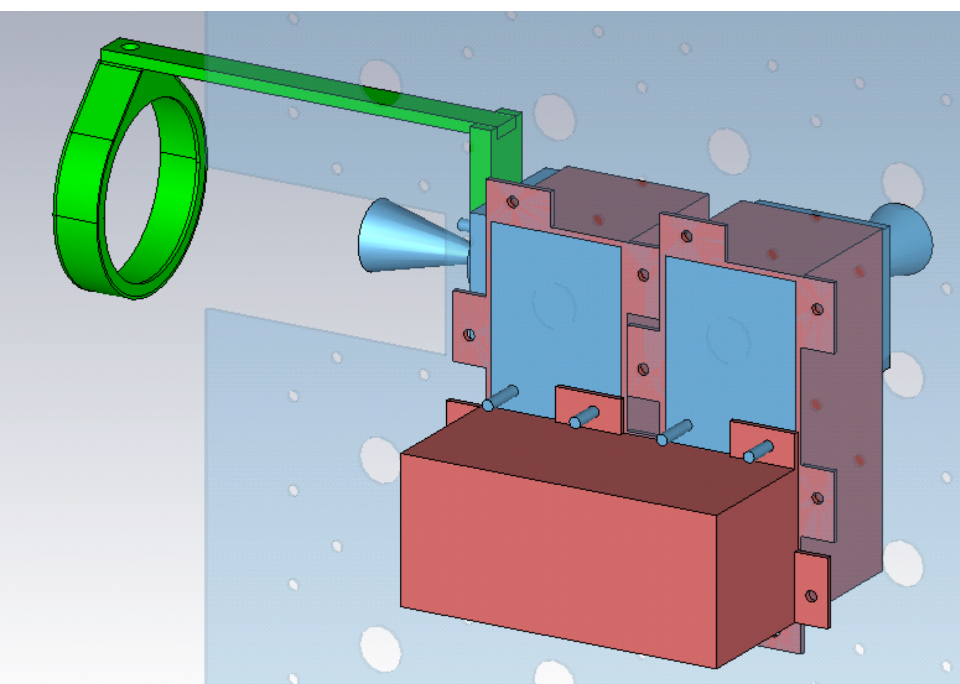
3-cavity cascade

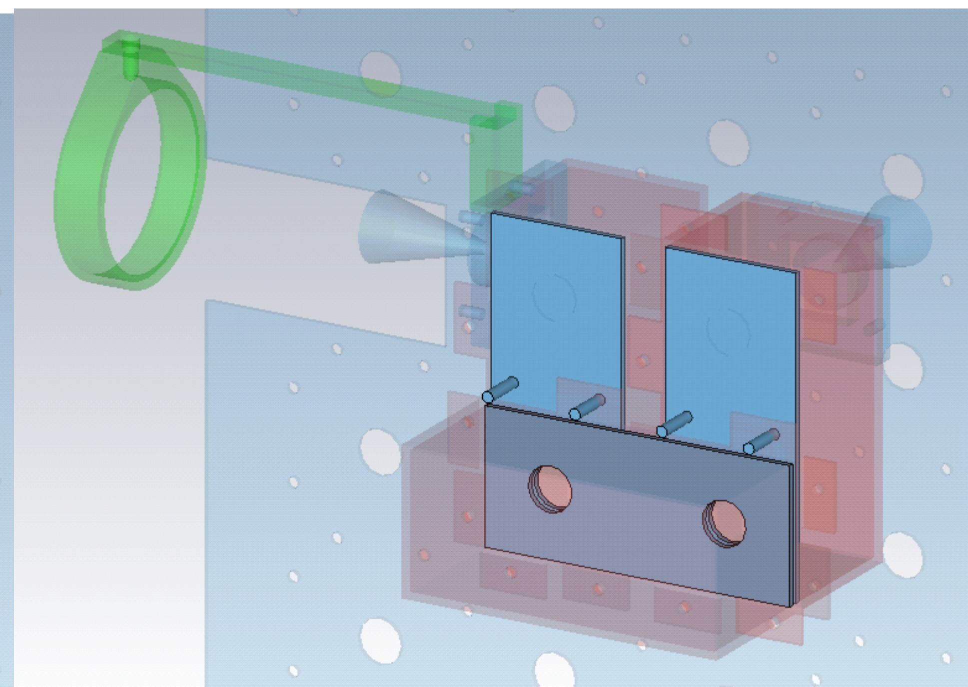
Perpendicular port

Lens for perpendicular port will be added later

Parallel port







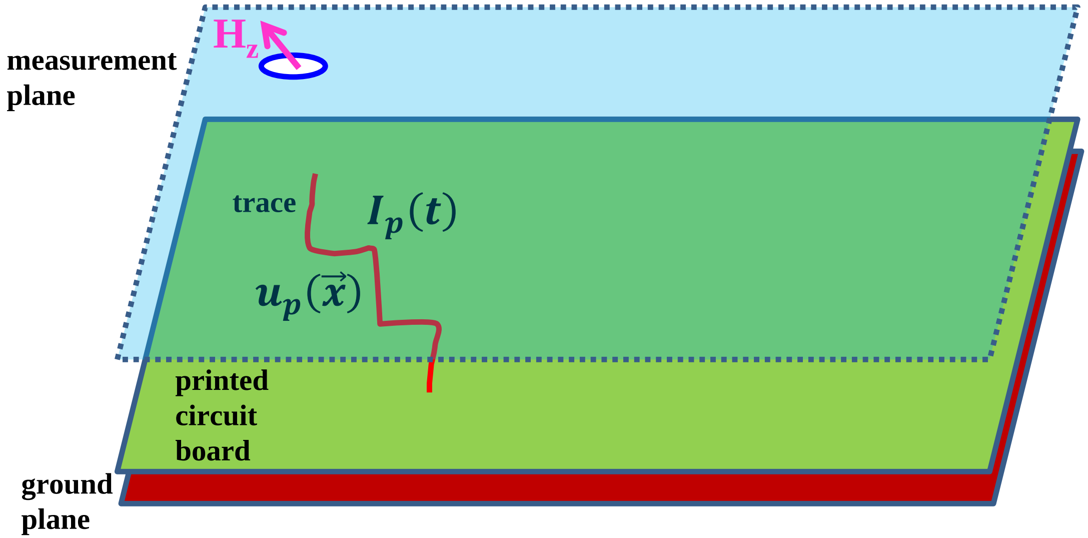
Outline

- The Issue: Electromagnetic Interference
- Our Approach – A Wave Chaos Statistical Description
- The Random Coupling Model (RCM)
- Example of the RCM in Practice
- Scaled measurement system for investigating new RCM predictions
- Extension of the RCM to Stochastic Sources
- Conclusions

Extend RCM to Describe Stochastic Sources Located in Enclosures

1. **Define a Radiation Impedance Z^{rad} for a spatially-extended and time-dependent source**

2. **Determine the Radiation Impedance from measured fields near the source**

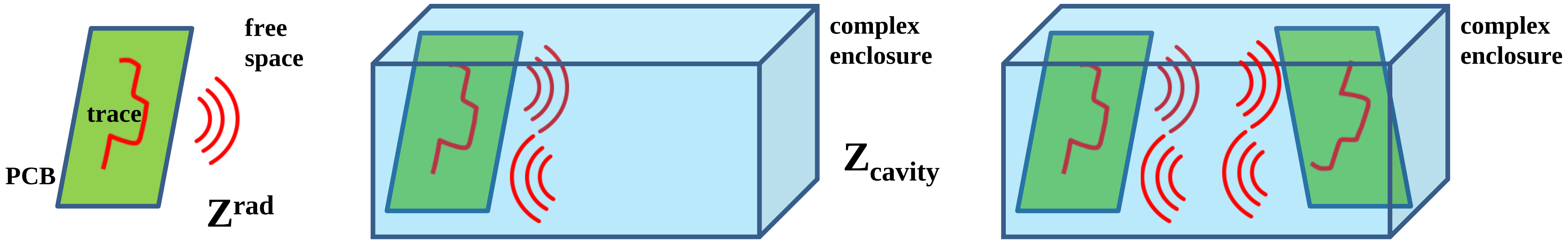


$H_z(\vec{x})$ **measurements determine** $u_p(\vec{x})$

Calculate Z^{rad}

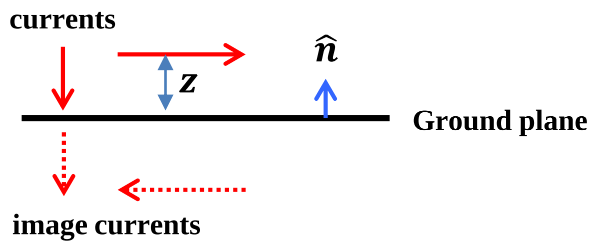
3. **Create the RCM statistical Z_{cavity} for the PCB in an enclosure**

4. **Calculate the interaction of one stochastic source with another through an enclosure**



Details of Extending RCM to Describe Stochastic Sources Located in Enclosures

A “port” now becomes a current trace and it’s image in the ground plane



$\boldsymbol{I_p(t), u_p(\vec{x})}$ **is the current trace profile function**

In principle one can use measurements of $\boldsymbol{H_z(\vec{x})}$ to deduce the trace profiles $\boldsymbol{u_p(\vec{x})}$

The radiation impedance can be written in terms of the trace profiles $\boldsymbol{u_p(\vec{x})}$

FT of the trace profile

$$Z_{pp'}^{rad}(k_0=\omega/c)=\frac{1}{2}\sqrt{\frac{\mu}{\varepsilon}}\int\frac{d^3k}{(2\pi)^3}\frac{ik_0}{k_0^2-k^2}\;\bar{\mathbf{u}}_p^*(\boldsymbol{k})\underline{\underline{\Delta}}_1\cdot\bar{\mathbf{u}}_{p'}(\boldsymbol{k})$$

$$\underline{\underline{\Delta}}_1=\frac{\mathbf{1}k^2-\mathbf{k}\mathbf{k}}{k^2}+\frac{\mathbf{k}\mathbf{k}}{k^2k_0^2}(k_0^2-k^2)$$

The cavity impedance expression is the same as before, except for the updated $\boldsymbol{Z^{rad}}$ and correlations between the random coupling variables

$$\underline{\underline{Z}}^{cav}=i\,\mathrm{Im}\left(\underline{\underline{Z}}^{rad}\right)+\left[\underline{\underline{R}}^{rad}\right]^{1/2}\cdot\underline{\underline{\xi}}\cdot\left[\underline{\underline{R}}^{rad}\right]^{1/2}$$

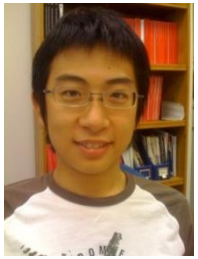
$$\underline{\underline{\xi}}=\frac{i}{\pi}\sum_n\frac{\Delta k^2\;\underline{w}_n\underline{\tilde{w}}_n}{(k_0^2-k_n^2)}$$

w_n are zero mean, unit width, un-correlated Gaussian random variables

All trace-to-trace correlations are built in to Z^{rad}

The Maryland Wave Chaos Group

Graduate Students (current + former)



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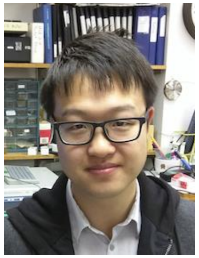

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Conclusions

The Random Coupling Model constitutes a comprehensive (statistical) description of the wave properties of wave-chaotic systems in the short wavelength limit

We believe the RCM is of value to the EMC / EMI community for predicting the statistics of induced voltages on objects in complex enclosures, for example.

Extension to Stochastic Sources looks promising

A new measurement system employing scaled structures enables new extensions of RCM:

- **Multiple connected enclosures**
- **Irradiation through irregular apertures**
- **Systems with mixed (regular and chaotic) properties**
- **Systems with evanescent coupling**

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ONR/DURIP

AFOSR / AFRL Center of Excellence

RCM Review articles:

G. Gradoni, *et al.*, Wave Motion <u>51</u>, 606 (2014)
Z. Drikas, *et al.*, IEEE Trans. EMC <u>56</u>, 1480 (2014)

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