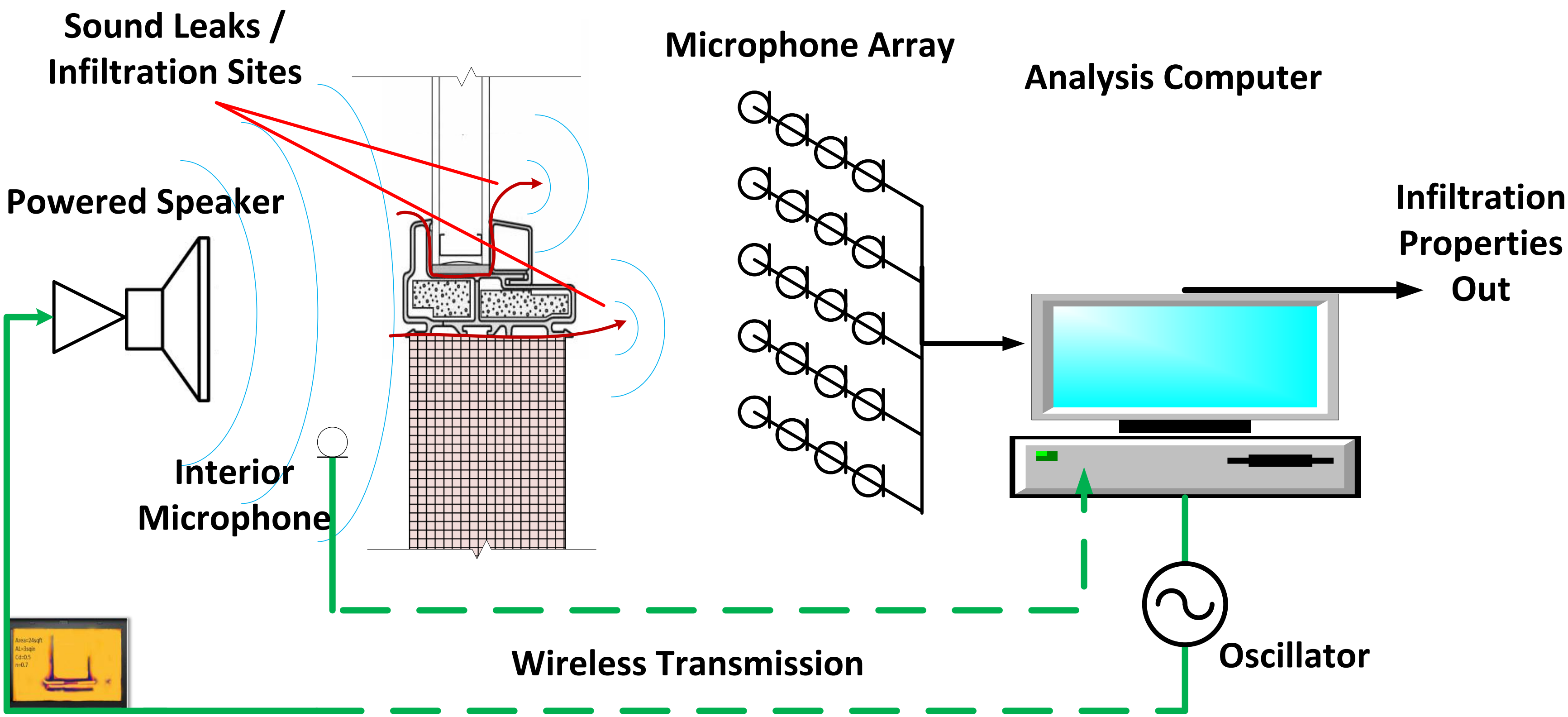
Acoustic Building Infiltration Measurement System (ABIMS): New Project

2014 Building Technologies Office Peer Review



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Argonne National Laboratory

Project Summary

Timeline:

Start date: 10/1/2014

Planned end date: 9/30/2015

Key Milestones

1. Full Computer Simulation: 9/30/2014
2. First Prototype Lab Test: 6/1/2015
3. First Prototype Field Test: 8/1/2015

Budget:

Total DOE $ to date: $650K

Total future DOE $: $0

Target Market/Audience:

Infiltration measurement companies; construction contractors; commissioning agents

Key Partners:

Illinois Institute of Technology

Argonne National Laboratory · Illinois Institute of Technology

Project Goal:

Develop a new building infiltration measurement system using acoustics to replace blower door and trace gas testing.

The new system will be capable of being used on commercial buildings of all sizes and at all stages of construction completion.

Purpose and Objectives

Problem Statement:

- Infiltration represents a significant portion of a buildings heating and cooling loads, especially in heating climates.
- Infiltration measurement of commercial buildings is difficult so building energy code does not require infiltration measurement to show compliance.
- Commercial energy code levels for infiltration are set higher than code developers would prefer, in part because of the inability to measure it.
- Weatherization of existing commercial buildings is more difficult because of the inability to quantitatively measure infiltration to quantify savings.

Target Market and Audience:

- Target market is the entire commercial building market
- Infiltration accounts for up to 0.7 quad of waste energy annually.
- The specific target audience is firms that provide infiltration measurement, building commissioning, and building weatherization.

Purpose and Objectives

Impact of Project:
- The main outcome of this project is a new technique for measuring building infiltration and the development of a prototype ready for commercialization

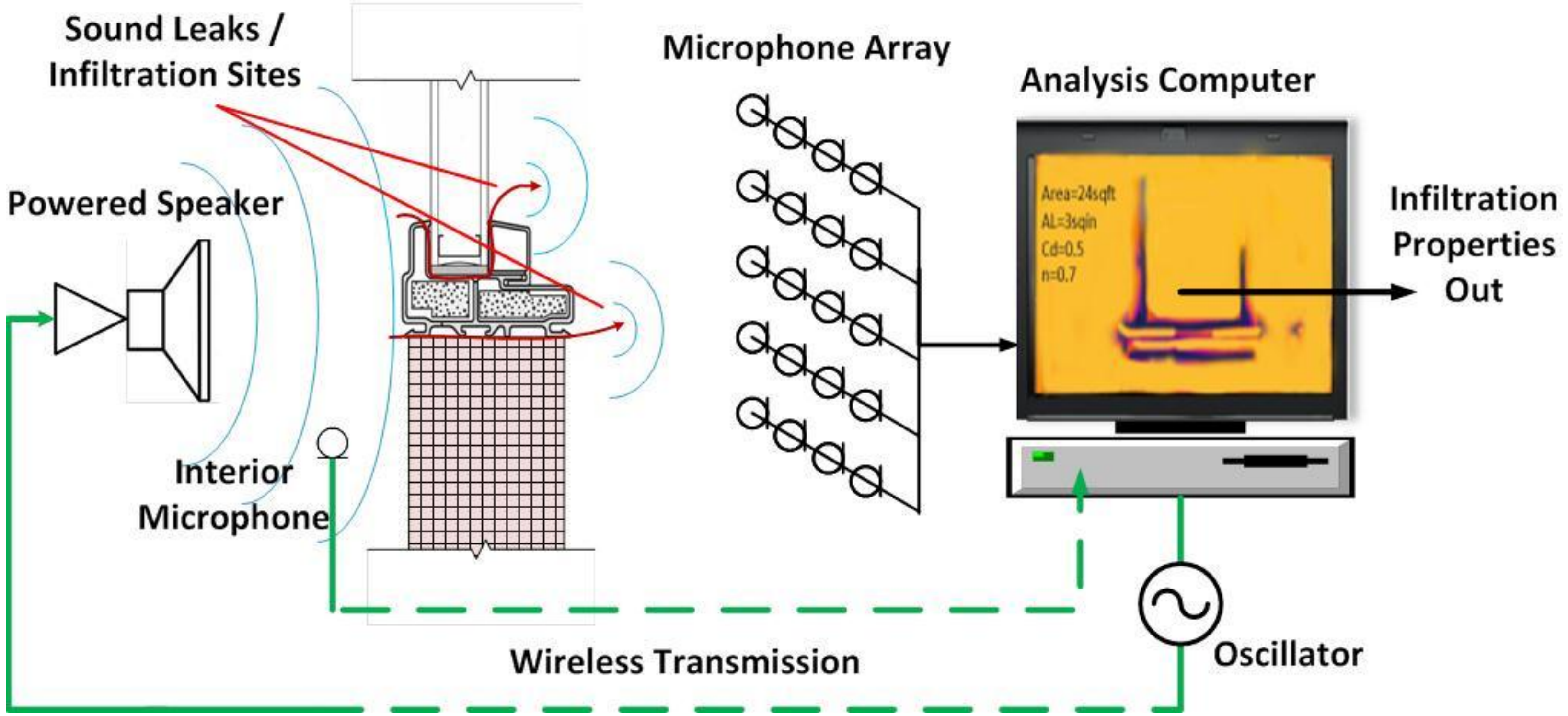
This will be a *disruptive technology* because it will make quantitative infiltration measurement on all commercial buildings practical for the first time.   This will
- Enable stricter infiltration rates in building energy code
- Improve compliance with code
- Allow quantitative assessment of energy savings from weatherization and infiltration reduction of existing buildings which is required to justify and finance such retrofits

Achievement will be measured by
- Near Term: Patent Application Approved
- Short Term: Commercialization of the technology within 2-3 years of end of project
- Long Term: Adoption of the technology by industry and changes to building code

Approach

Approach:

- ABIMS ensonifies a portion of a building enclosure, measures the sound leakage using an advanced acoustic measurement technique and uses the acoustic properties to estimate the infiltration properties



Approach

Key Issues:

- Need to quantitatively measure acoustic properties of leaks at a distance.
  - At a distance is necessary to make measurements practical and low cost.

- Need to be able to take measurements with other intruding sounds present
  - Want to be able to measure during construction or when occupied.

- Need to develop relations between acoustic properties and infiltration properties of an enclosure section.
  - Relations required to get infiltration information from acoustic data.

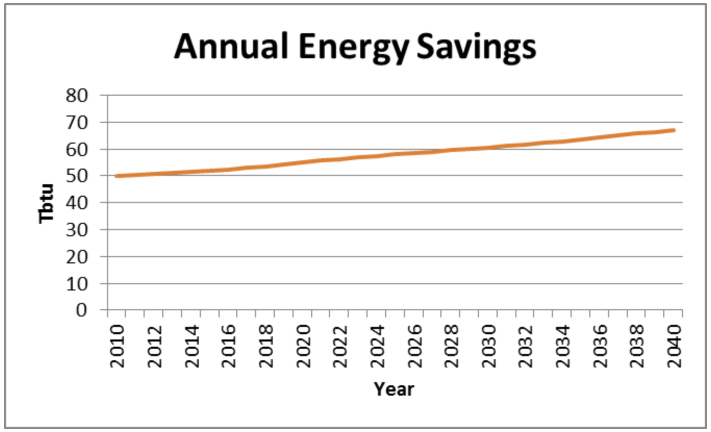
Distinctive Characteristics:

- We will use patent pending advanced acoustic measurement techniques to isolate and quantify the acoustic properties of the leaks, reject background noise, and convert acoustic properties to infiltration properties

Progress and Accomplishments

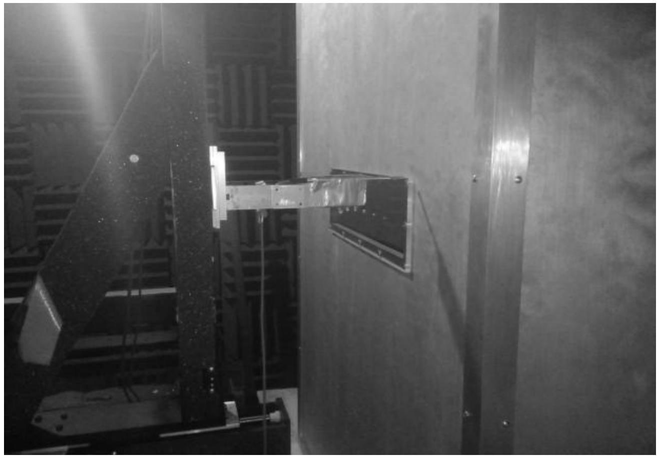
Technical Potential Energy Savings from Code Changes Estimated

- Technical Potential Energy Savings from infiltration code changes alone (no retrofits) was estimated to be in excess of 50 TBtu/yr
- Infiltration reduction from retrofits of old buildings will only increase this savings



Test Chamber Designed and Built

- Test chamber for controlled lab experiments completed ahead of schedule



Other Progress

- Progress toward Q3 milestones (Analytic Work and Acoustic Measurement) are all on track

Market Impact

- None Yet

Awards/Recognition:

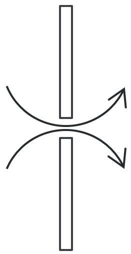
- Patent Application Started

Progress and Accomplishments

- Analytic Work: Redeveloped Classic Solutions for Infiltation

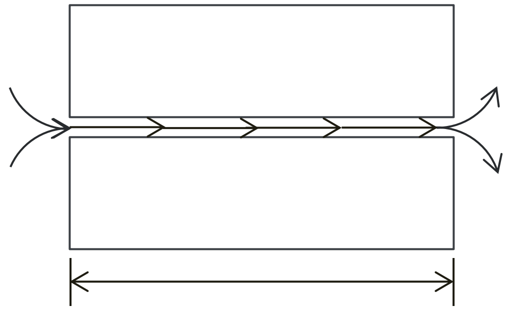
$$(\vec{v} \cdot \vec{\nabla})\vec{v} = -\frac{1}{\rho}\vec{\nabla}p + \nu\nabla^2\vec{v}$$

Hole in a thin plate



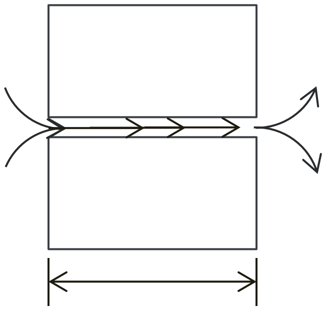
$$Q = \pi a^2 \sqrt{\frac{2}{\rho}}\Delta p^{0.5}$$

Hole in a very thick plate



$$Q = \frac{\pi a^4}{8\nu L}\Delta \mathrm{p}$$

General Crack



$$Q = C\Delta \mathrm{p}^{\mathrm{n}}$$

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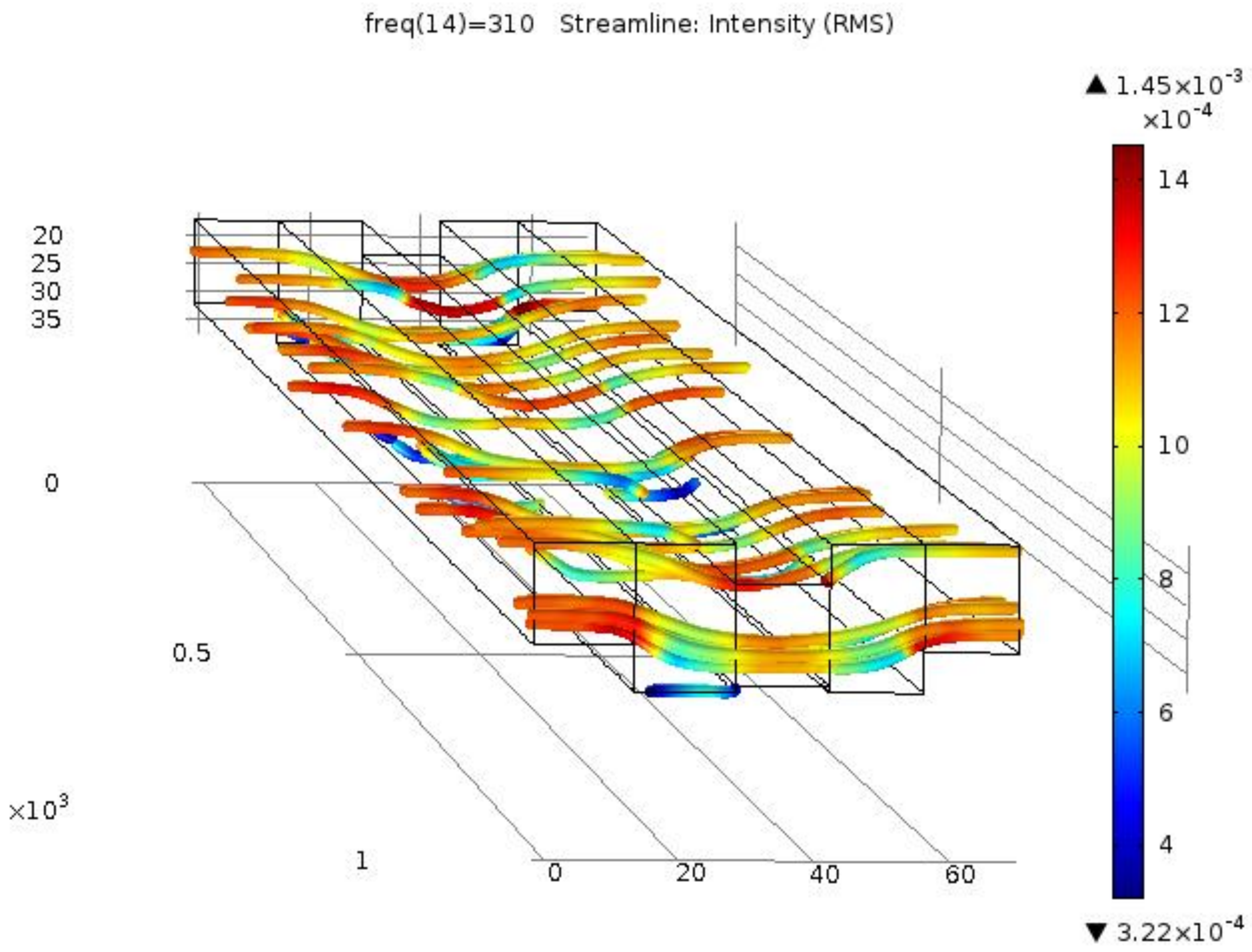
Progress and Accomplishments

- Acoustic Propagation Modeling with Comsol Multiphysics



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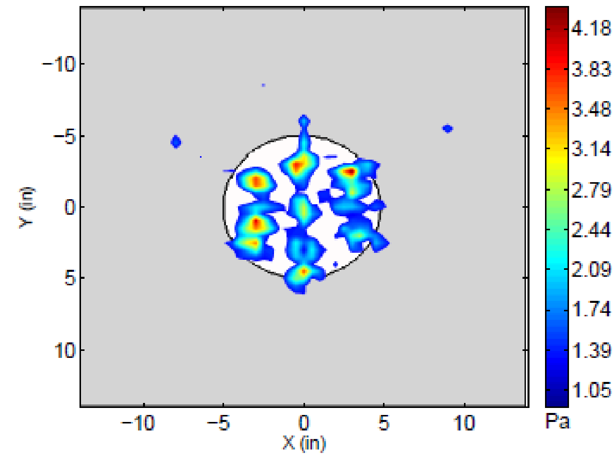
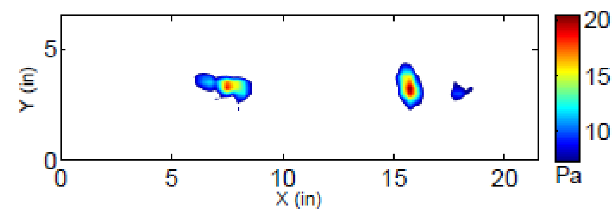
Progress and Accomplishments

- Measurement Algorithms

(a) Qualification test

(b) Leakage test





Project Integration and Collaboration

Project Integration:

- Argonne and IIT PIs are working with Argonne Technology Development and Commercialization to develop a patent

  Argonne's TDC will begin looking for commercialization partners when Q3 milestones are complete

Communications:

- Work will be presented at the Acoustical Society of America Spring 2014 Meeting and at the ASME 2014 Fluids Engineering Summer Meeting

Acoustical Society of America

ASME

Project Integration and Collaboration

Partners

- IIT is the only project partner.

  IIT is working with ANL to help develop the array measurement technique, construct the prototype, and perform the lab/field tests

Team Members

- Argonne: Ralph T Muehleisen, Eric Tatara
- IIT: Ganesh Raman, Kanthasamy Chelliah, Hiren Kumar Patel




Next Steps and Future Plans

Q3 FY14: Completion of analytic relations between acoustic and infiltration properties and measurement algorithms and acoustic measurement algorithms

Q4 FY14: Simulation of complete system completed and used to test potential performance as well as determine individual component requirements.   Three potential commercialization partners identified.

Q2 FY15: First Prototype Complete and Tested in Lab

Q3 FY15: Prototype Field Experiments Complete

Q4 FY1Y: Commercialization Partner Engaged and Technology Licensed

REFERENCE SLIDES

Technical Potential Savings From Code Changes

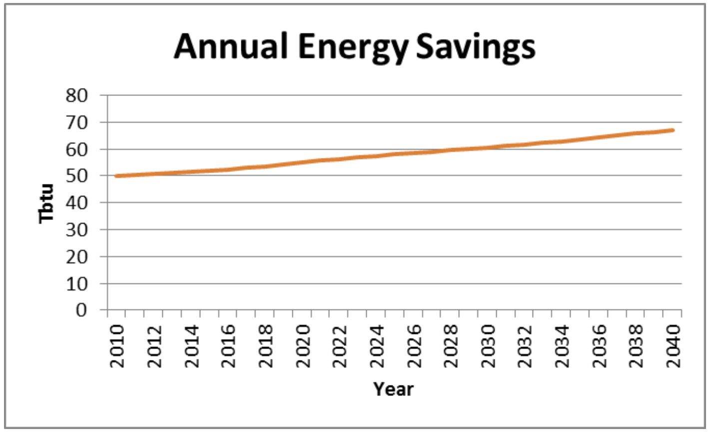
- Infiltration in current commercial building energy code
  - No whole building maximum infiltration rate (unlike residential) only component maximums
  - No requirement to test infiltration rate for compliance (unlike residential)
  - PNNL developed a baseline infiltration rates[1] for code models based on ASHRAE Envelope Subcommittee guidelines added to ASHRAE 90.1 [1].
  - ASHRAE Envelope subcommittee recommends that code require whole building infiltration rates which are about75% lower than their current component rates but concedes that until infiltration can be practically measured code should be changed
  - IMT estimates that less that only fraction of new buildings are actually compliant with the infiltration rate requirements[2] so we estimate that average infiltration rates are about 50% more than the PNNL baseline rates.
- Assumed code changes from ABIMS
  - Measurement allows infiltration rates to be reduced to envelope subcommittee recommended levels and will increase compliance so we estimate that the average infiltration rate will be 50% lower than the current rate PNNL uses for code models

[1]Gowri, K, DW Winiarski, and RE Jarnagin. 2009. "Infiltration Modeling Guidelines for Commercial Building Energy Analysis." In *PNNL Report PNNL-18898*.

[2]Sarah Stellberg. 2013. "Assessment of Energy Efficiency Achievable from Improved Compliance with U.S. Building Energy Codes: 2013 – 2030". *Institute for Market Transformation Report, Feb 2013.*

Technical Potential Savings From Code Changes

- Analysis Method
  - Used PNNL ASHRAE 90.1 2010 methodology, building models , climates, and weightings[1]
  - Adjusted existing reference building infiltration levels up 50% to account for the lack of compliance with current code to estimate current energy use.
  - Adjusted existing reference building infiltration levels down by 50% to account for new code levels and higher compliance rates enabled by ABIMS to estimate energy use after code changes from ABIMS.
  - In total, 512 Energy Plus runs were made to estimate energy savings in 2010.
  - Difference between existing and new code levels was used to estimate energy savings for 2010
  - EIA estimates of commercial building stock growth was used to determine yearly savings through 2030.

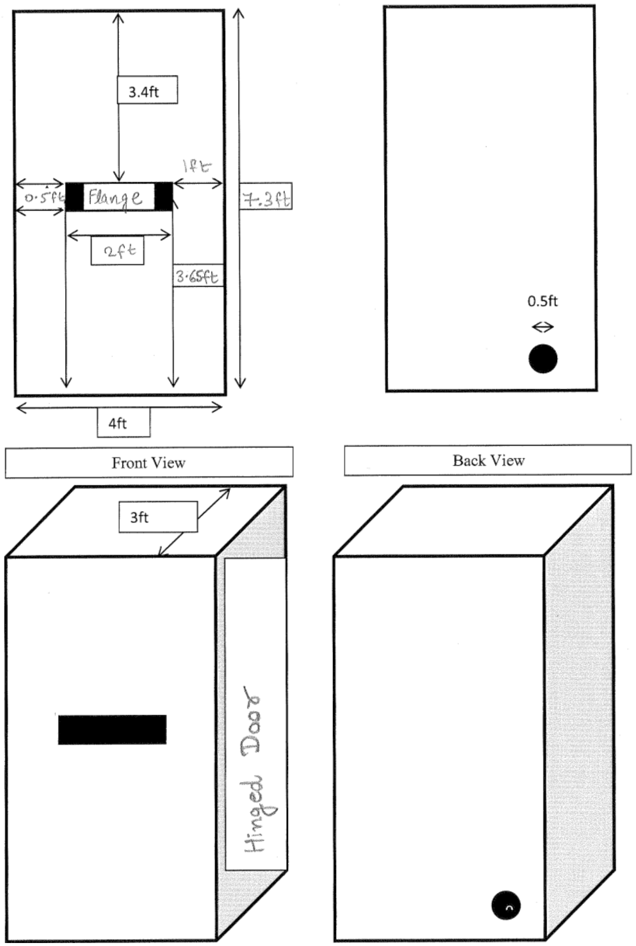


- Results
  - Infiltration code changes in 2015 could generate energy savings in excess of 50 Tbtu/yr, 0.9 quad cumulative from 2015-2030

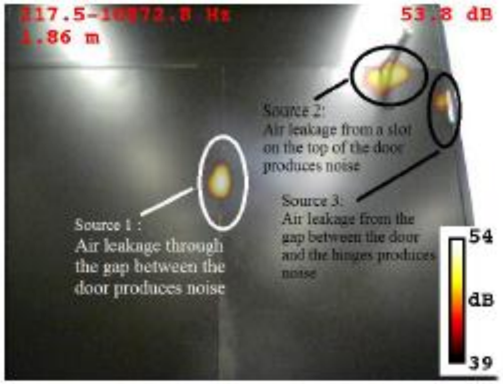
[1]Thornton, BJ, *et al*. 2011 , "Achieving the 30% Goal: Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010." In *PNNL Report PNNL-20405.*

Acoustic Measurement System

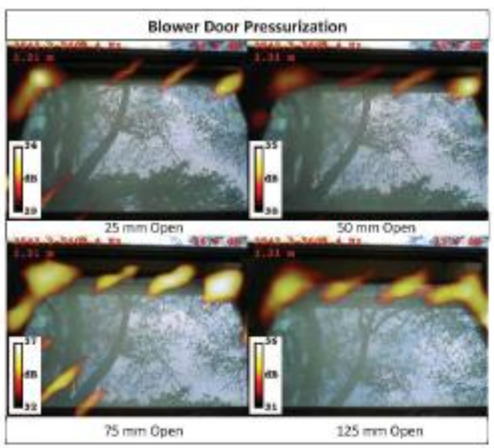
- Algorithmic development is ongoing
  - IIT working closely with ANL to adapt
- Close in tests of preliminary algorithms with raw speakers and test chamber inserts are promising
  - Algorithms are done in MATLAB
  - Single microphone measurements are pieced together to simulate Array



IIT's Previous Work on Leak Location



(a) A leaky door



(b) Blower door test

(c) Synthetic acoustic source test

Time domain Beamforming (TIDY) maps of (a) the top half of a leaky door, (b) a leaky window of a pressurized building, and (c) a building that houses a loudspeaker. The leakages are located by yellow spots in the maps.

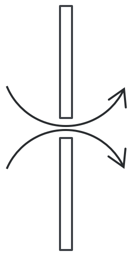
Analytic Infiltration

- Analyze infiltration as incompressible static flow using 1-D flow equation is 1-D Navier-Stokes

$$(\vec{v} \cdot \vec{\nabla})\vec{v} = -\frac{1}{\rho}\vec{\nabla}p + \nu\nabla^2\vec{v}$$

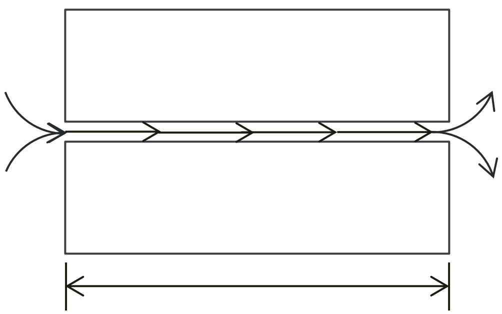
  - Analyze extremes for a hole of radius *a* and area *A* in a wall

<u>Hole in a thin plate</u>



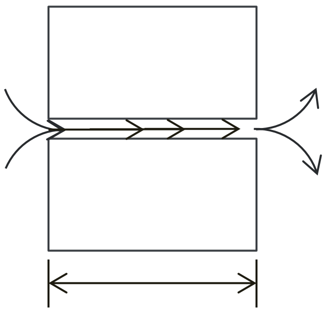
$$Q = \pi a^2 \sqrt{\frac{2}{\rho}}\Delta p^{0.5}$$

<u>Hole in a very thick plate</u>



$$Q = \frac{\pi a^4}{8\nu L}\Delta \mathrm{p}$$

<u>Hole in a general plate</u>



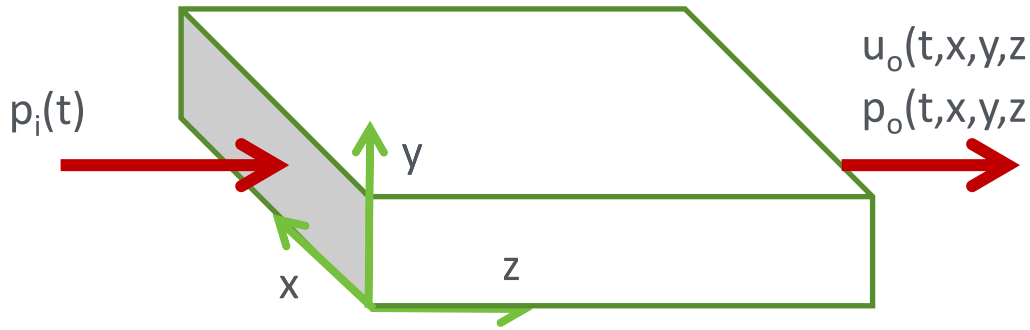
$$Q = C\Delta \mathrm{p}^{\mathrm{n}}$$

Analytic Evaluation of 3D Wave Equation

- The wave equation in 3D rectilinear coordinates derived from the mass continuity and dynamical equilibrium equations for an inviscid fluid:

$$\left[\frac{\partial^2}{\partial t^2} - a_0^2\, \nabla^2\right] p = 0$$

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$



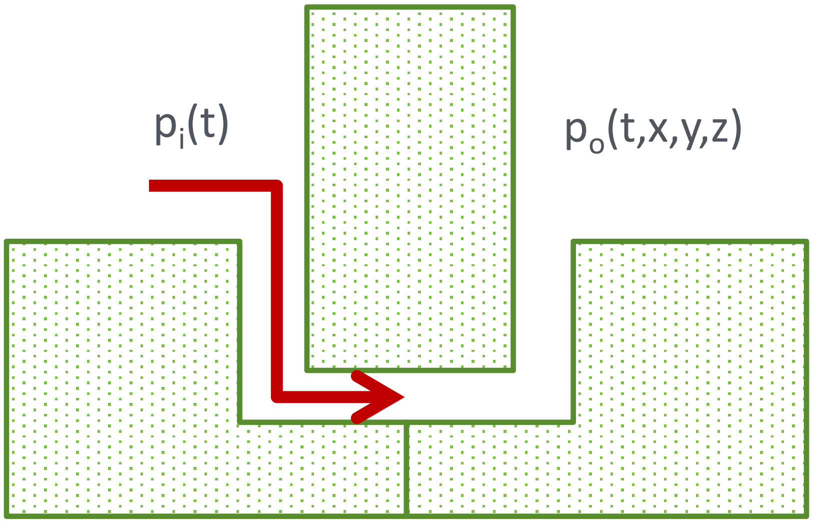
- In the case of plane wave propagation in a duct or tube, the pressure is invariant along dimensions other than the dimension perpendicular to the plane wave (tube axis). The general solution to this 1D case is:

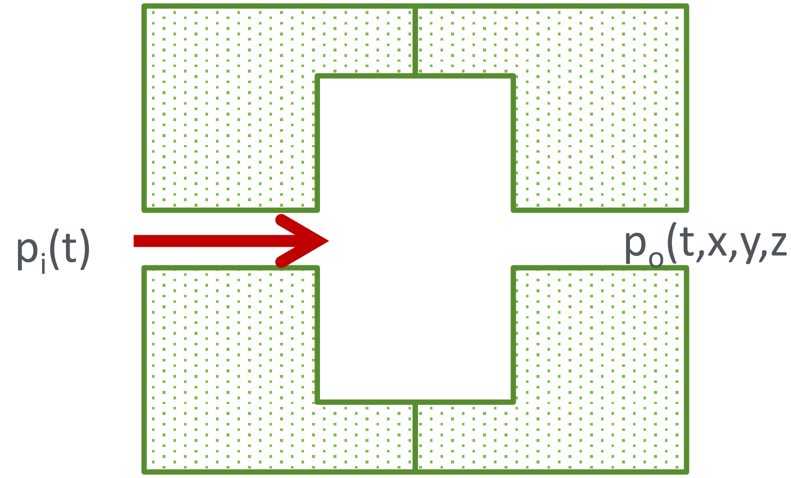
$$p(t,z) = C_1 e^{j\omega\left(t - \frac{z}{a_0}\right)} + C_2 e^{j\omega\left(t + \frac{z}{a_0}\right)} \qquad \omega = 2\pi f \qquad a_0 \cong 340\ \mathrm{m/s}$$

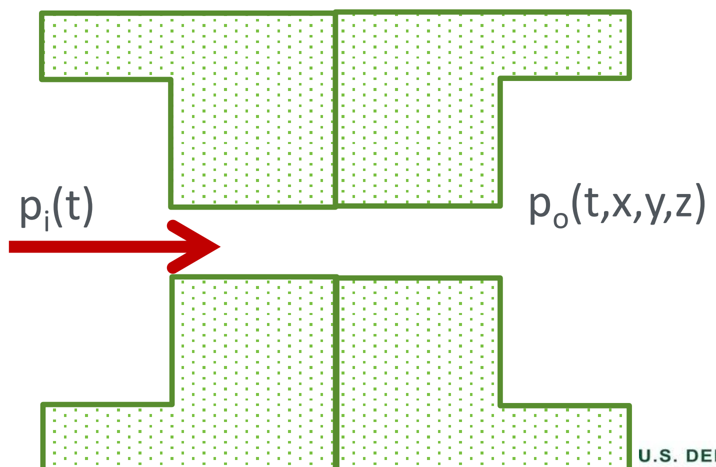
- For short and straight cracks, the opposing wave component (C_2) can be neglected such that the 1D wave equation for pressure and velocity simplifies to:

$$p(t,z) = C_1 e^{j\omega\left(t - \frac{z}{a_0}\right)} \qquad u(t,z) = \frac{1}{Z_0}\left(C_1 e^{-jkz}\right) e^{j\omega t}$$

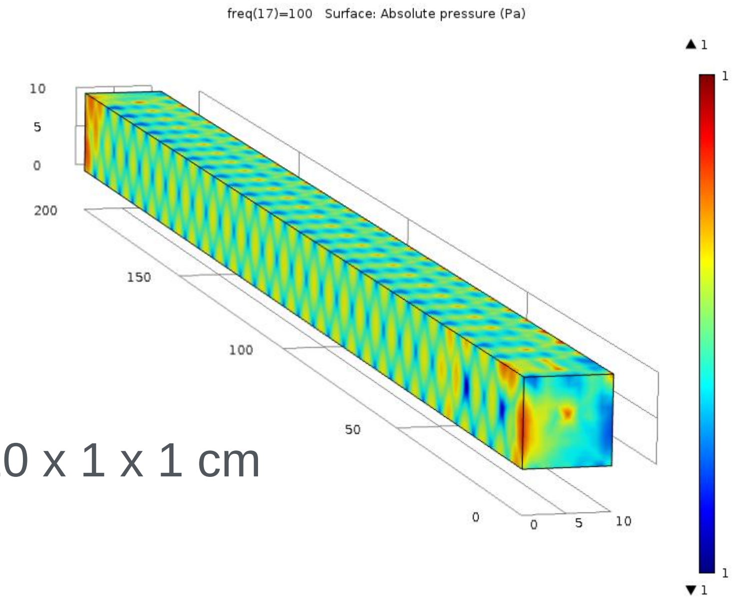
Crack Geometries to Evaluate



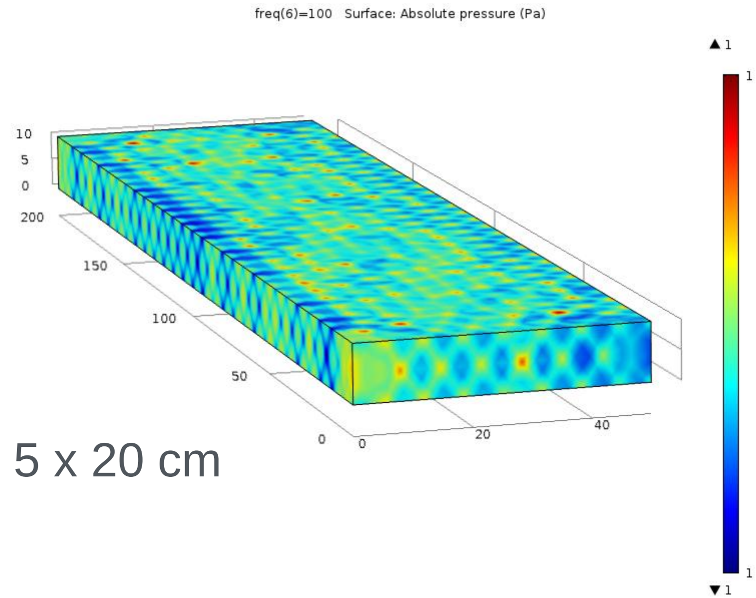




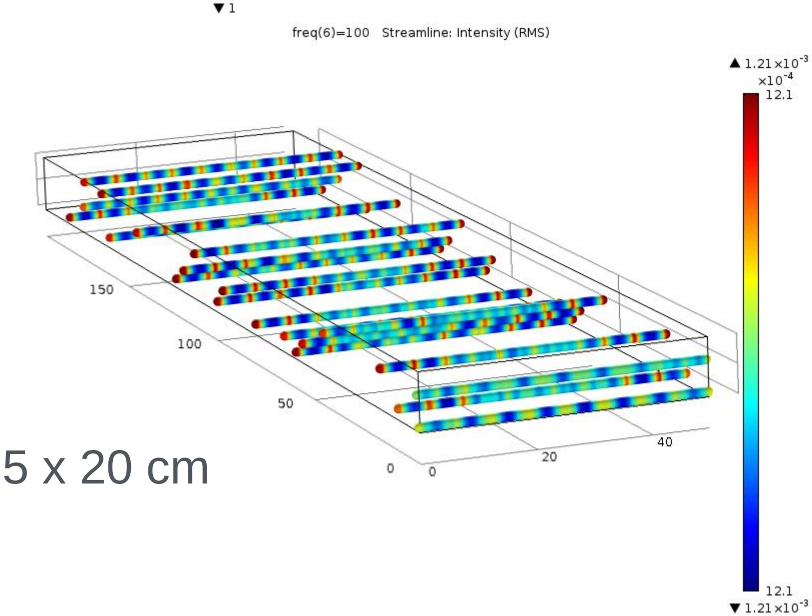
Numerical Solution of PDE with COMSOL



20 x 1 x 1 cm



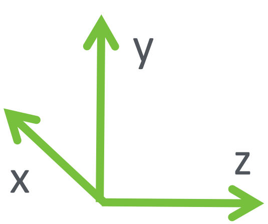
20 x 5 x 20 cm



20 x 5 x 20 cm

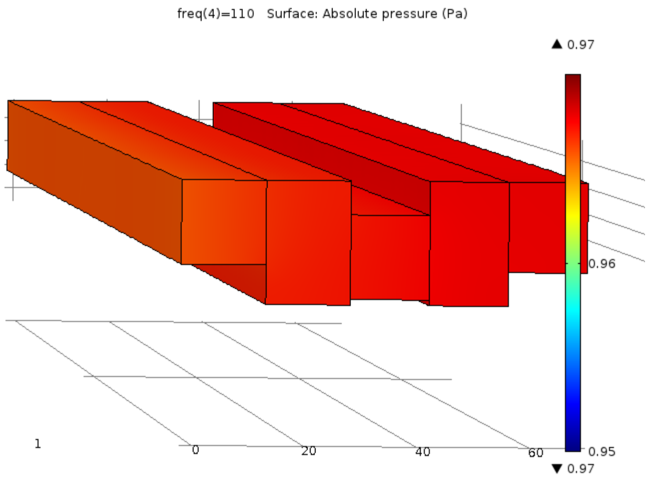
For all cases:

- p_0= 1 Pa
- f = 100 Hz

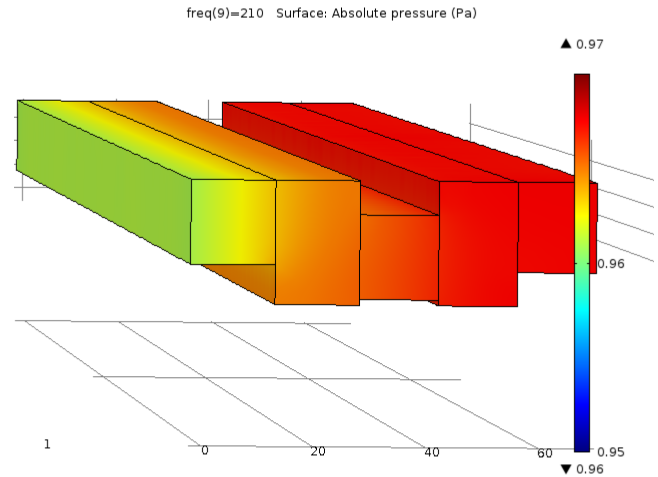


Acoustic Pressure: Frequency parameter sweep

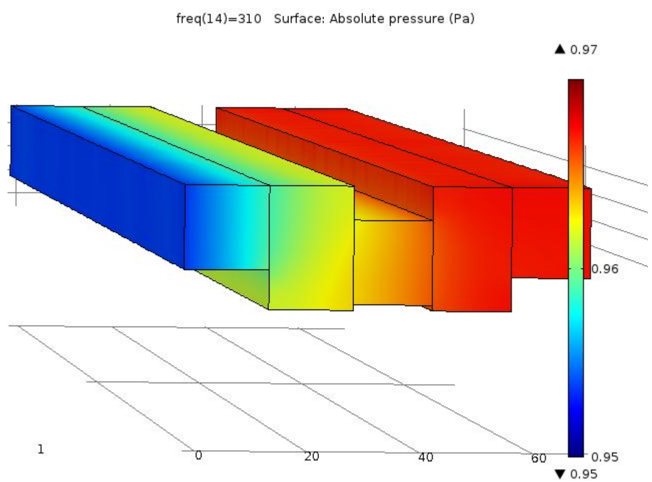
110Hz



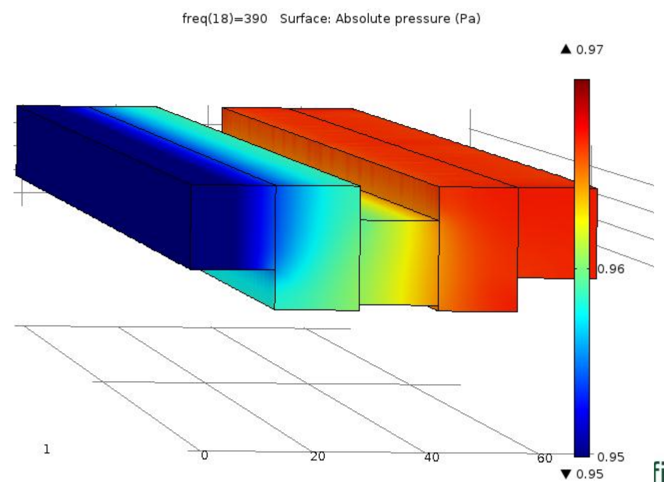
210Hz



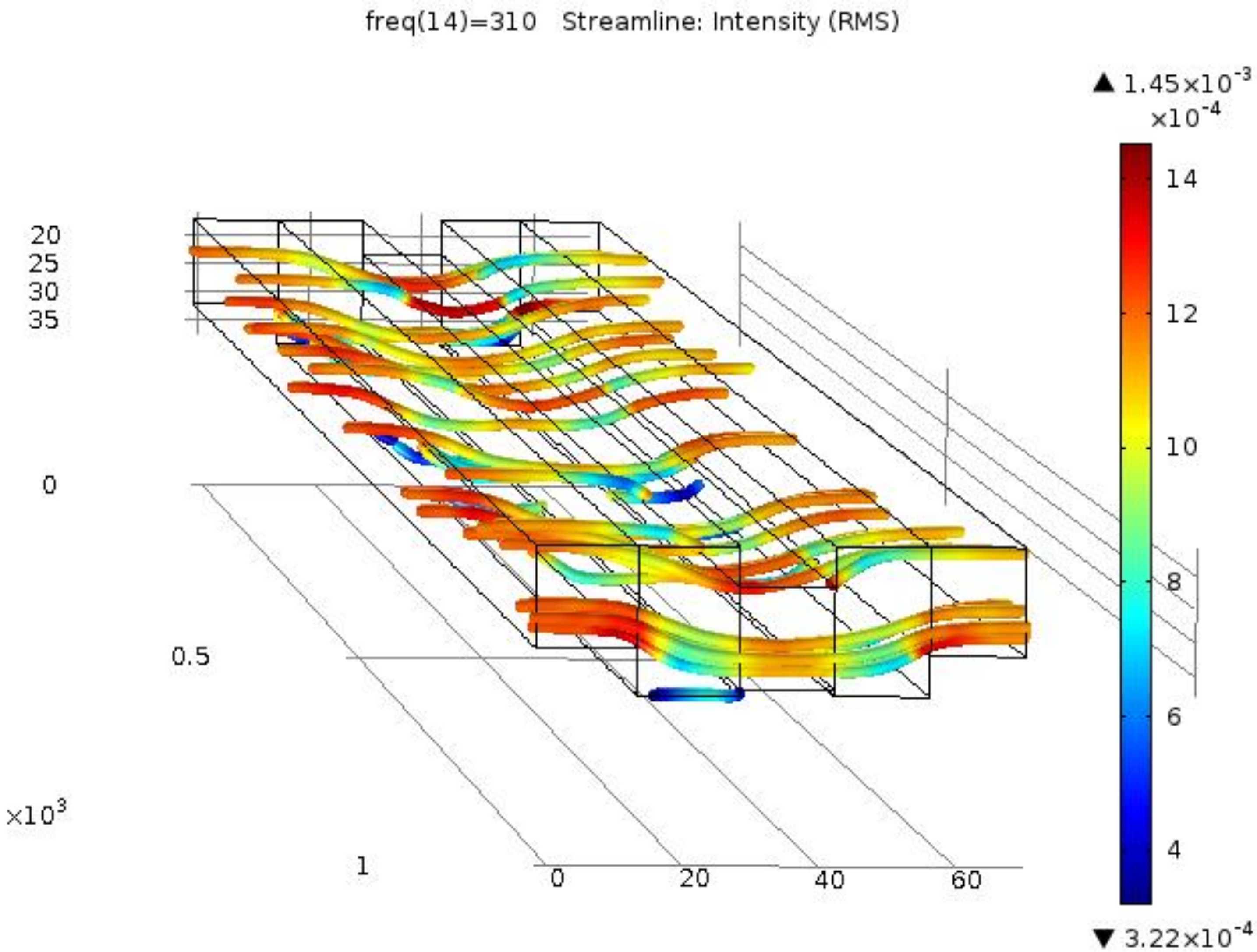
310Hz



390Hz



Crack Flow Streamlines



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Project Budget

Project Budget: $325K in FY14, $325K in FY15
Variances: None
Cost to Date: $112K + $265K Encumbrance for IIT Subcontract
Additional Funding:

- IIT Partner had a previous small grant from the National Collegiate Inventors and Innovators Alliance (NCIIA) to study measurement of building leakage using acoustic beamforming .
- IIT providing cost share through tuition reduction.

Budget History					
FY2013 (past)		FY2014 (current)		FY2015 – 9/31/2015 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$325K	$17k	$325K	$17k

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Project Plan and Schedule

Project on schedule and all deliverables on time as of March 25, 2014

Project Schedule												
Project Start: 10/1/2013		Completed Work										
Projected End: 9/31/2015		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned) use for missed										
		Milestone/Deliverable (Actual) use when met on time										
	FY2013				FY2014				FY2015			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Technical Potential Energy Savings from Code												
Develop Design Specification												
Current/Future Work												
Develop Analytic Relations												
Develop Mic Array Processing Algorithms												
Test Chamber Construction												
Full ABIMS Simulation												
Determine Full Energy Savings for Ptool												
Prototype Development												
Lab Testing												
Field Testing												
License Technology to Industry												