Development of Radio Frequency Diesel Particulate Filter Sensor and Controls for Advanced Low-Pressure Drop Systems to Reduce Engine Fuel Consumption (06B)

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ID#: ACE089

Overview

Timeline

- **Project Start: July 2012**
- **Project End: June 2015**
- **Percent Complete: 25%**

Barriers

- **Emission controls are energy intensive and costly**
- **Lack of "ready-to-implement" sensors and controls**
- **Durability of 120K miles for LD and 435 K miles for HD**

Need sensors and controls to exploit efficiency potential of CIDI engines!

Budget

- **Total Funding: $2,564,850**
  - DoE Share: $1,999,884
  - Contractor Share: $564,966
- **Government Funding**
  - Funding in FY12: $162,259
  - Funding for FY13: $631,018*

  * Budgeted FY2013

Partners

- **Department of Energy**
- **Corning** – *Advanced DPFs*
- **Maguffin Microwaves** - *Electronics*
- **Oak Ridge National Lab** - *Testing*
- **FEV** – *Controls Development*
- **Detroit Diesel** – *Tech. Adviser*
- **DSNY (New York)** – *Fleet Testing*

Relevance – Project Objectives

Develop RF Sensor for accurate measurements of diesel particulate filter (DPF) loading with advanced low ΔP systems.

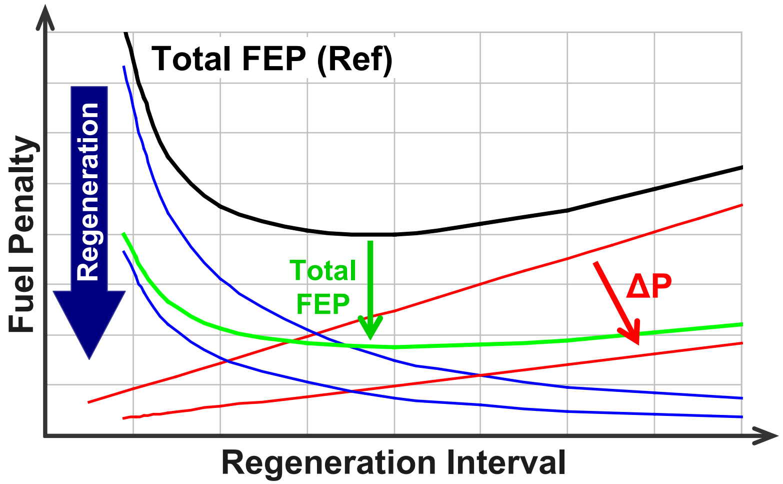
Address Technical Barriers to reduce fuel consumption via optimization of combined engine-aftertreatment system while reducing emissions, system cost, and complexity.

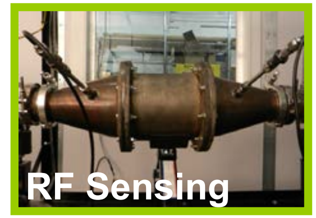
The specific project objectives included:

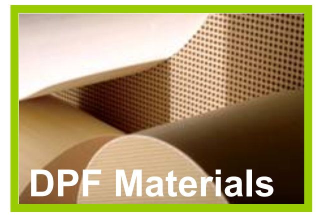
1. **Research & develop RF sensor for direct measurement of DPF load;**
2. **Quantify improvements in efficiency and greenhouse gas reduction via improved sensing, controls, and low- ΔP components;**
3. **Push the limits to achieve breakthrough efficiencies with advanced combustion modes, alternative fuels, and advanced aftertreatment enabled by improved sensing and controls;**
4. **Develop production designs and commercialization plans on the scale to significantly impact greenhouse gas and fuel consumption.**

Relevance – Proposed Technology and Concept

Motivation: Enable reduced energy consumption, cost, and increased durability of particulate filter systems through improved sensing and controls.



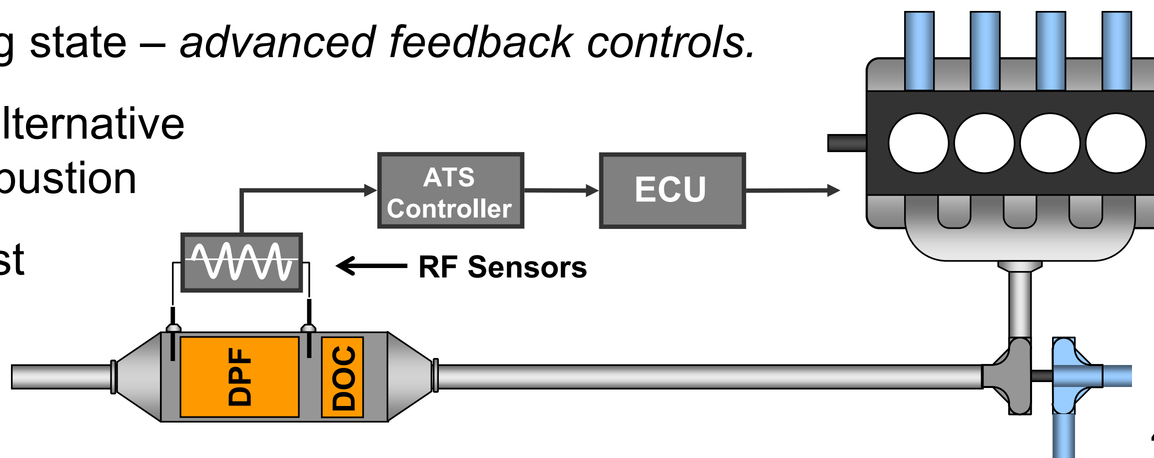




Advanced Controls

Concept: Apply inexpensive radio frequency (RF) technologies to directly monitor DPF soot and ash levels and distribution with low-ΔP DPF materials.

- Direct measure of loading state – *advanced feedback controls.*
- Additional benefits with alternative fuels and advanced combustion
- Large benefit per unit cost
- Applications for OBD



Relevance – Project Milestones FY12 & FY13

FY 2012 Milestones	Status
Phase 1 - Sensor Development	
1.1 Complete Initial Updates to Project Management Plan	Complete

FY 2013 Milestones	Status
1.2 Initial Simulation and Modeling Complete	Complete
1.3 Initial Sensor Designs Complete	Complete
1.4 Final Protoype Component Selection	Complete
1.5 Sensor Prototype Complete	Complete
1.6 Initial Prototype Sensor Calibration Complete	Started
1.7 Prototype Baseline Characterization Complete	Started
1.8 Phase 1 Report Complete and Submitted to DOE	Not Yet Started
Phase 2 - Sensor Testing	
2.1 Error Sources Identified	Not Yet Started

Current Status: Finalizing prototype sensor development and calibrations.

Next Steps: Distribution of sensors to partners for extended testing.

Approach – Highly Integrated

Leverage prior work by FST developing RF-based DPF sensing technologies and controls:

- Prior work with NSF (fundamental science) and ORNL evaluating alpha prototype; ongoing testing with OEM customers
- Results of previous R&D efforts and OEM customer input have defined test plan and objectives for this program

Close collaboration with RF electronics design firm to develop beta prototype system supplied to partners:

- In-house calibration development, analysis of noise factors, system optimization, and modeling at **FST**
- Application of RF-sensors with advanced DPF materials includes engine dyno and vehicle testing with **Corning**
- Controls architecture development and benchmarking against existing pressure and model-based systems by **FEV**
- Investigation of application with advanced combustion modes, alternative fuels, and PM instrumentation at **ORNL**
- Extended field testing (48 months) with HD diesel fleet at **DSNY**
- Independent technical review and input provided by **DDC**

Technical Approach – Overview & YEAR 1

I: Research & Development → **II: Performance Evaluation** → **III: System Level Dev. and Testing** → **IV: Pre-Production Design**

Phase I: RF Sensing Research and Development

TASK 1.0 Project Management and Setup of Test Systems

- Setup and validation of experimental facilities (test cell commissioning)

TASK 2.0 Design RF Prototype Sensors

- RF modeling and system simulations to guide prototype design
- Targeted experiments to support and validate models

TASK 3.0 Develop RF Prototype Sensors

- Component selection, component-level testing and prototype fabrication
- Software and algorithm development, signal processing

TASK 4.0 Begin Prototype Testing and Calibration

- Develop initial sensor calibrations (PM, ash, distribution)
- Final sensors supplied to project partners for testing

Accomplishments – Task 1 Test Systems Setup

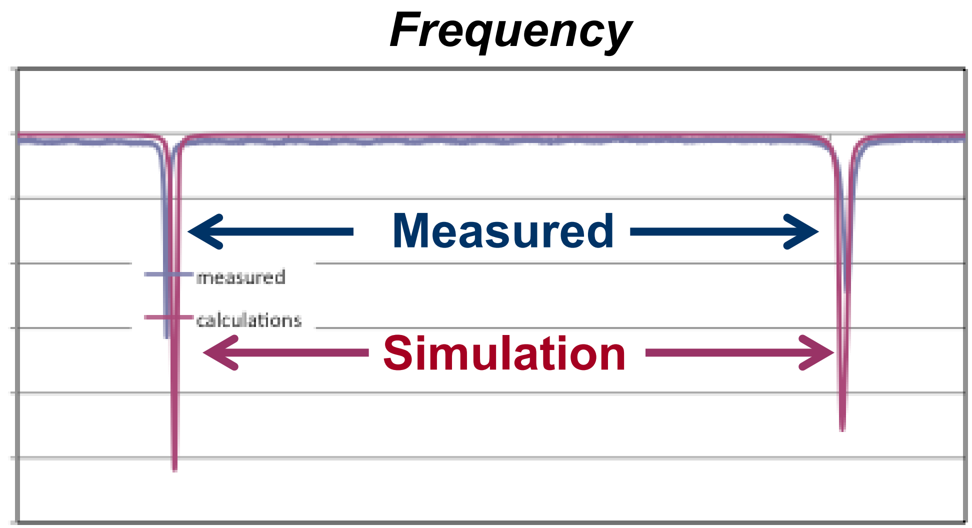
Test Cell Installed and Commissioned - *enables careful control of DPF soot loading quantity, spatial distribution, and ash aging for calibration development and RF signal analysis.*

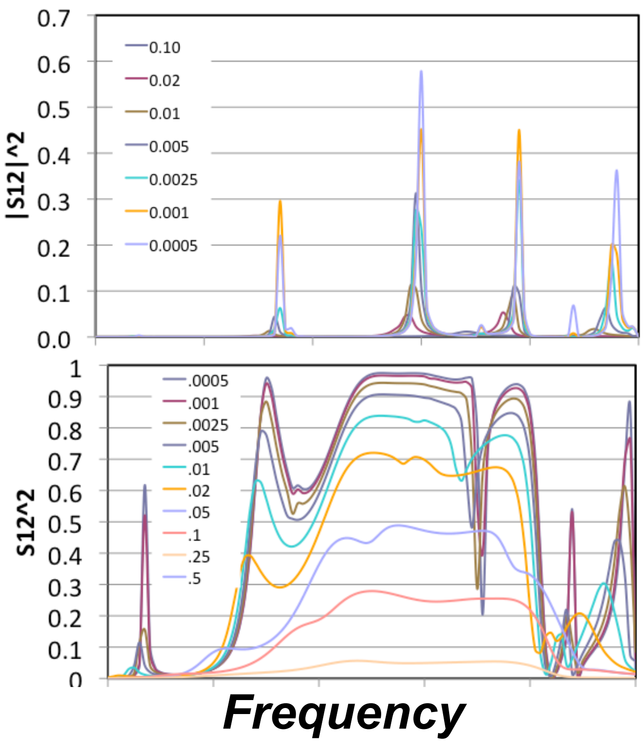
FST Facilities Setup and Commissioning Complete

- RF electronics fabrication and test systems include vector network analyzers, custom fabricated test cavities, and control/simulation software
- Test cell includes Kubota D905 diesel engine for DPF soot loading
- Additional burner-based accelerated DPF aging and ash loading systems simulate approx. 150K on-road miles in less than 1 month
- Partner facilities include LD and HD engine dynos, test vehicles, and advanced PM measurement instrumentation for sensor benchmarking and evaluation

Accomplishments – Task 2.A. RF Models Guide Design

- **Developed fundamental RF filter simulations**
- **Validated models with cavity experiments and network analyzer**





Applied simulations to guide fundamental system design

- Conducted parametric studies to optimize antenna design
- Understand sensitivity of soot and ash dielectric properties as a function of temperature and frequency
- Evaluate sources of variability on overall signal response

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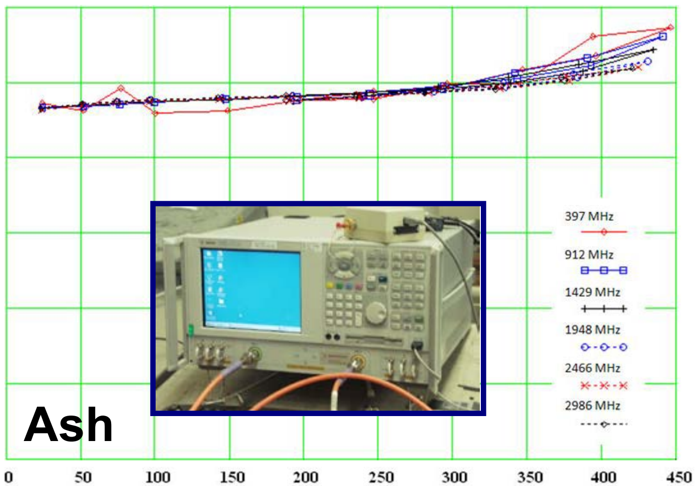
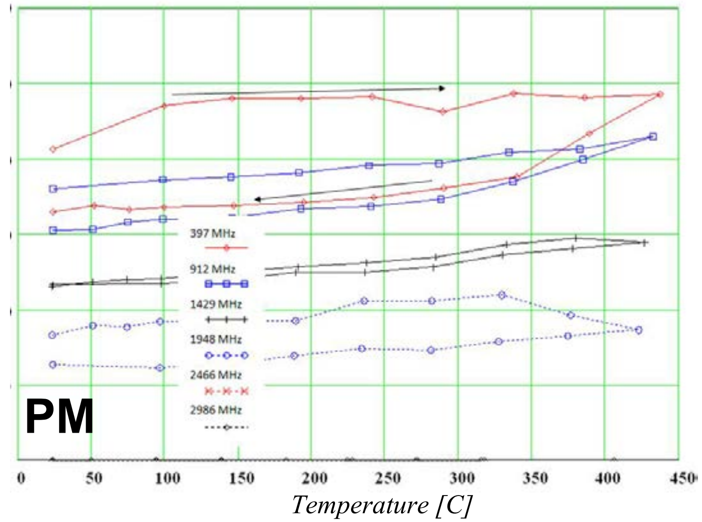
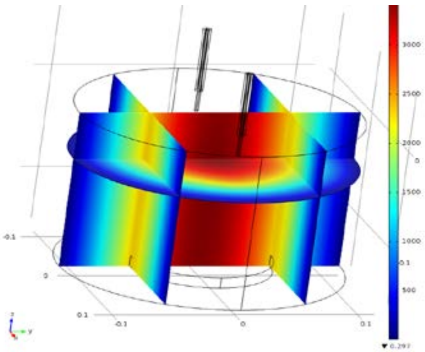
Accomplishments – Task 2.B. Dielectric Measurements

Detailed understanding of soot and ash dielectric properties critical input to models and interpretation of RF signal.

- Characterized soot and ash over temperature and frequency range at various packing densities.
- Fabricated 3 custom RF cavities to cover full frequency range of interest.
- Combined approach utilized vector network analyzer measurements and cavity perturbation models.
- Ash shows much lower degree of temperature and frequency sensitivity than soot.







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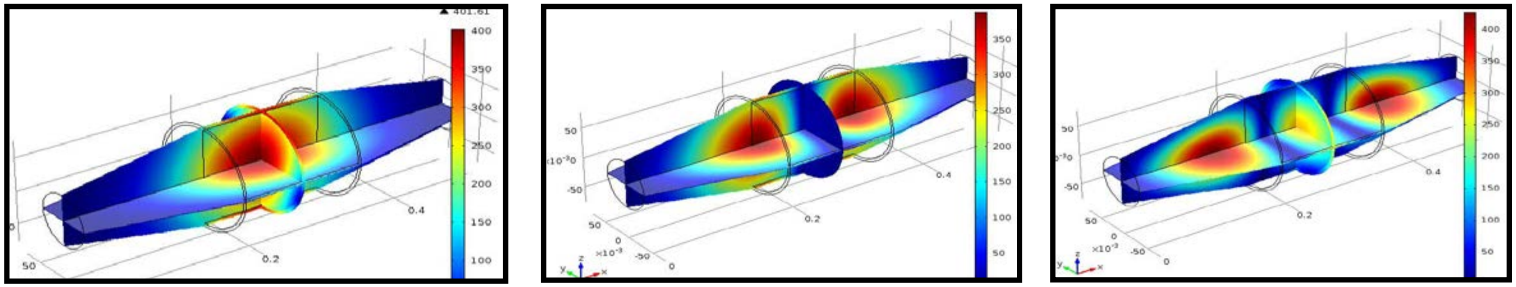
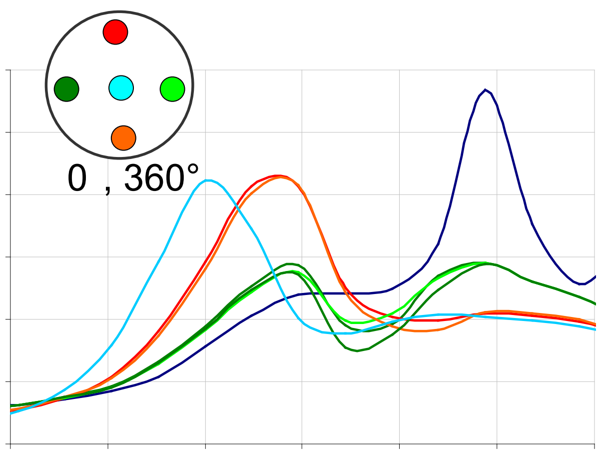
Accomplishments – Task 2.C. Spatial Distribution

- **Models completed for 5.66” diameter cordierite DPF**
- **Results show electric field (spatial resolution) variation with frequency**



- **Bench testing to evaluate impact of local PM loading on RF signal**
- **Additional simulations developed for alternative cavity geometries**

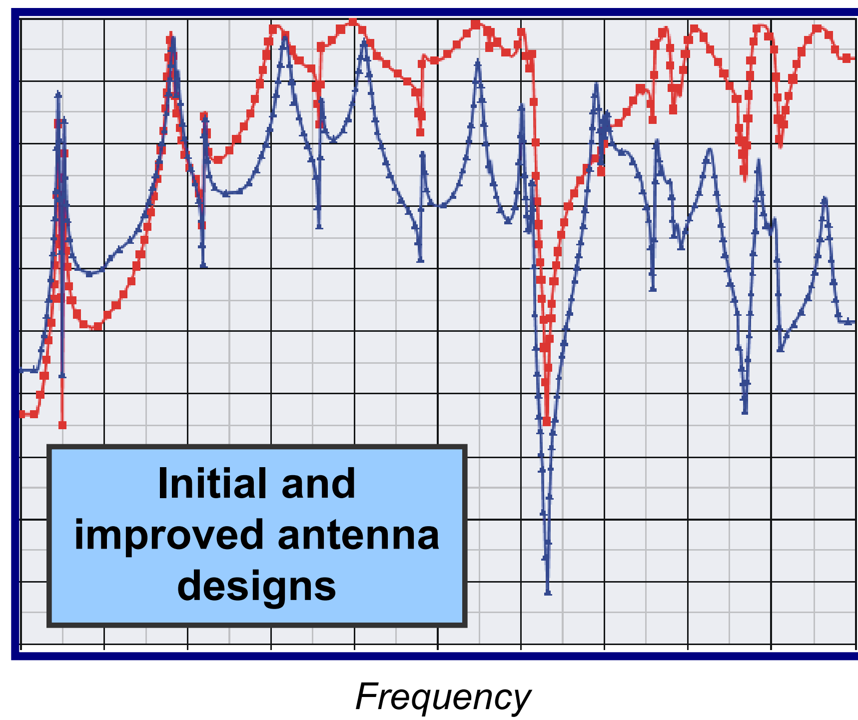


Radial Distribution

- Monitor frequency range sufficient to generate multiple resonant modes in DPF housing (resonant cavity)
- Electric fields associate with each mode used to monitor local state of filter loading (accumulation or regeneration)
- Additional calibration activities ongoing

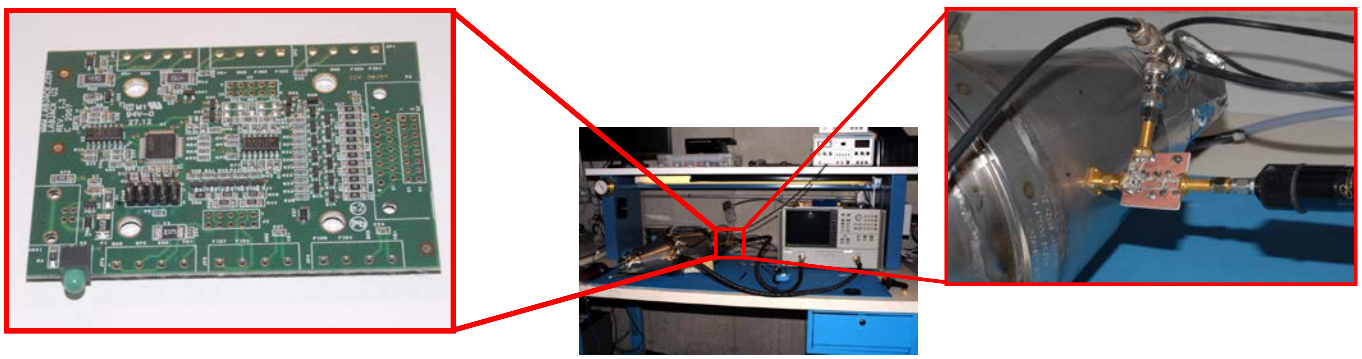
Accomplishments – Task 3.A. RF Antenna Design

- Clean slate approach taken to optimize RF antenna design
- Fabricated and tested various antenna configurations to cover required bandwidth for specific filter geometry
- Developed improved means for coupling RF signal across frequency range
- Considered sensor performance and practical (robust) form factor
- Finalized antenna design and investigated improved antenna materials
- RF simulations incorporate final antenna geometry



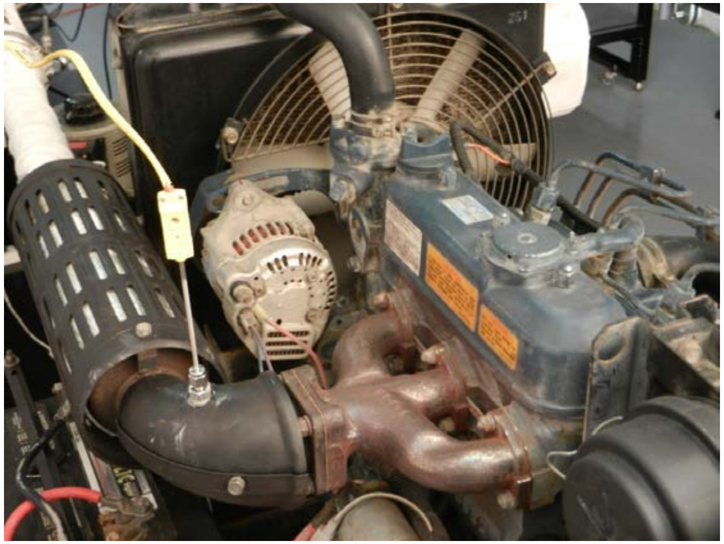
Accomplishments – Task 3.B. Sensor Electronics

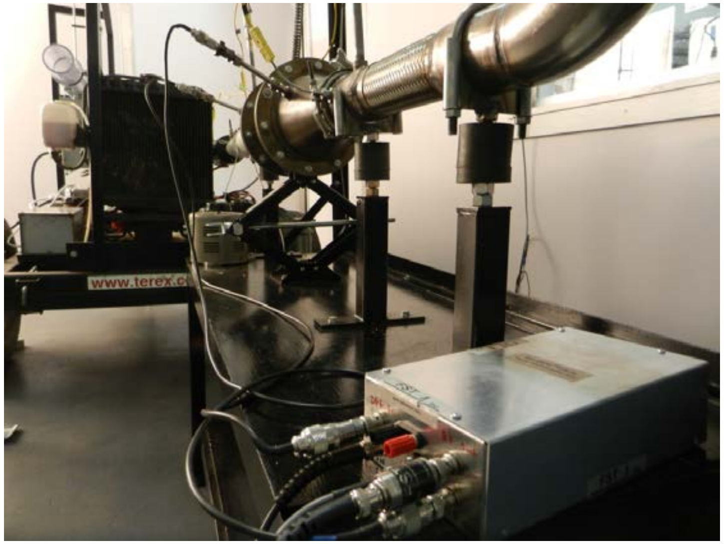
- **Evaluated performance/complexity trade-off between vector and scalar RF electronics and measurement system**
- Defined operating system performance requirements
  - *Measurement accuracy and dynamic range* ***– Extended measurement range***
  - *Response time and frequency range* ***– Improved response times***
  - *Repeatability and robustness given environmental requirements*



- **Completed design analysis considering performance requirements**
- RF electronics system breadboarded in several variants
- Breadboards evaluated via PC-controlled testing in test cell (ongoing)
- Form factor hardware developed by contract manufacturer

Accomplishments – Task 4.A. Engine Testing Started





Kubota Engine Specifications

- Model: D905
- Fuel: Diesel
- Power: 9.7 kW (13 hp)
- Speed: 1800 rpm
- Injection: IDI
- Cooling: Water
- Emissions: Tier 2 (pre-2006)*

Baseline Sensor Evaluation

- DPF instrumented with several antenna variations
- Performance evaluations with previous and next generation RF electronics
- Bench testing to evaluate RF signal transmission down exhaust pipe ~ 2” length sufficient for cutoff over frequency range of interest

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**Use of lower Tier engine enables faster soot loading and study of soot composition impacts*

Accomplishments – Task 4.B. Ash Aging System

Ash accumulation impacts fuel consumption and filter life (durability)

- Resulting soot spatial distribution influenced by location of ash
- Timescales of 100K+ miles generally required for ash build-up
- Impact of ash important consideration over lifetime of DPF

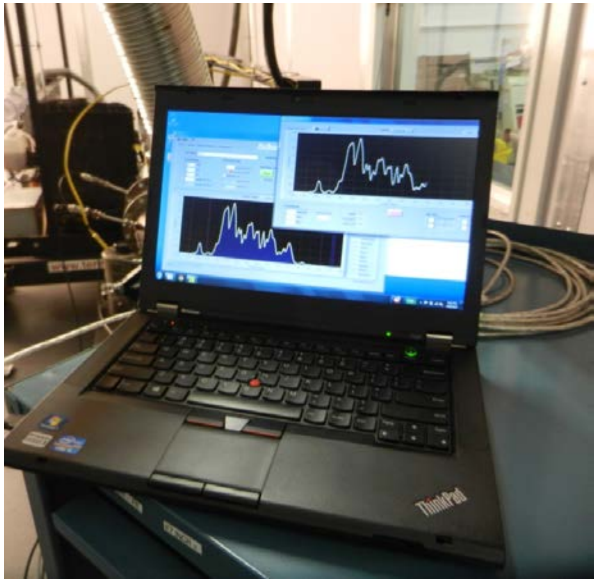
Accelerated ash loading and aftertreatment aging system

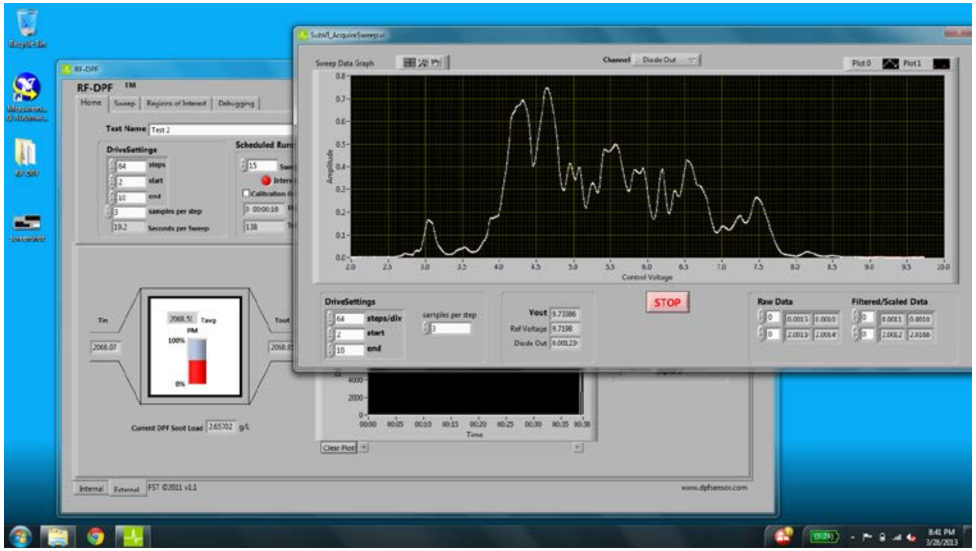
- Diesel and lubricant burner-based system previously validated at MIT
- Enables accelerated ash loading of over 150K on-road miles in less than one month of testing in the lab
- Applied to develop ash calibrations and evaluate ash impacts
- Allows for controlled thermal cycling and aging of RF sensor as well

Accomplishments – Task 4.C. Calibration Development

Calibration Software Development

- Software developed using existing National Instruments platform in Phase I
- Interface (UI) developed and allows for real-time display or raw RF signal and direct sensor control
- Enables fast and efficient calibration development and sensor performance testing
- Fully-integrated controller will be developed and implemented (smart sensor) in Phase III



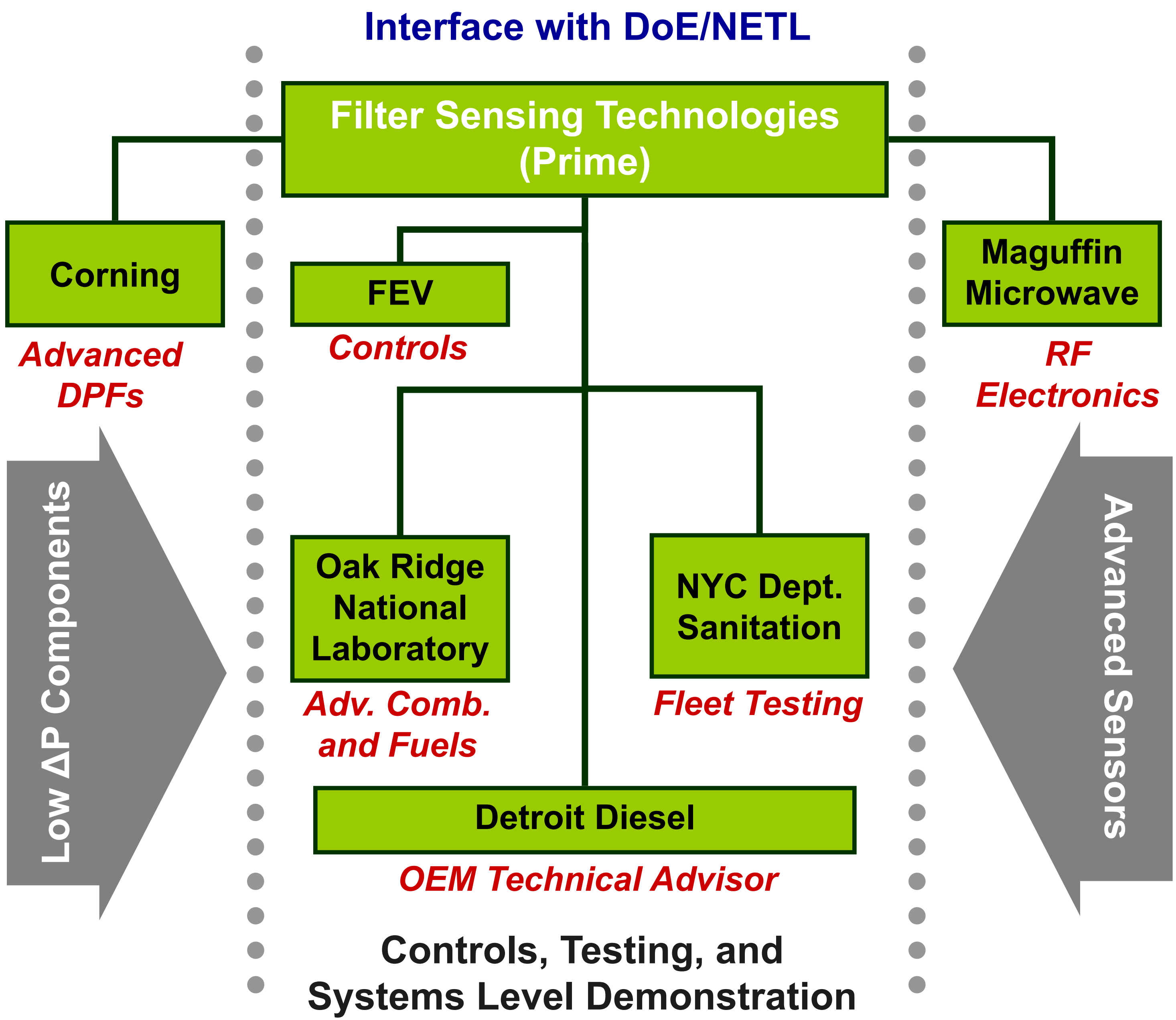


Screenshot showing raw RF signal and user interface

System Functionality

- Direct modification of sensor operating parameters (frequency, sweep speed, etc.)
- Fully-integrated data acquisition and signal processing
- Online temperature compensation capabilities
- Self diagnostics already built into system from ground up and important for OBD compliance

Collaboration and Project Coordination



Proposed Future Work

Phase I – Sensor Research and Development **2013**

- **Task 4.0** Calibration for soot, ash, and spatial distribution (FST)
- **Task 5.0** Baseline performance evaluation (ORNL/Corning/FST)

Phase II – Sensor Testing **2013 - 2014**

- **TASK 7.0** Noise factor and error source analysis and correction (FST)
- **TASK 8.0** Sensor accuracy evaluation with advanced DPFs
  - *Measurements in light- and heavy-duty applications (FST/Corning)*
  - *Sensor benchmarking with laboratory instruments (ORNL)*
  - *Kick-off first round of extended fleet testing (DSNY)*
- **TASK 9.0** Evaluate RF sensor with advanced combustion (ORNL)
- **TASK 10.0** Evaluate RF sensor with alternative fuels (ORNL)

Phase III – System Level Demonstration **2014 - 2015**

Second prototype iteration and controls (FST, MM, FEV, ORNL, Corning)

Phase IV – Commercial Planning **2014 - 2015**

Summary

Developing novel RF sensing and control technologies to address key barriers to improved engine efficiency and reduced emissions.

Accomplishements Since Program Inception 07/2012

- Setup and commissioned experimental test facilities
- Developed and validated RF system models to guide prototype design
- Conducted targeted experiments to characterize soot and ash dielectric properties as function of frequency and temperature
- Developed and tested several variations of RF sensing electronics
- Completed final prototype system for testing in Phase I and II
- Initiated engine testing and calibration activities

Outlook and Project Impact

- Results of Phase I provide extended measurement range, accuracy, and robustness for the developed prototype system
- Kicking off prototype testing with industry and national lab partners
- If successful, considerable potential to overcome barriers identified in VT Program Plan (2011-2015) through improved sensors and controls

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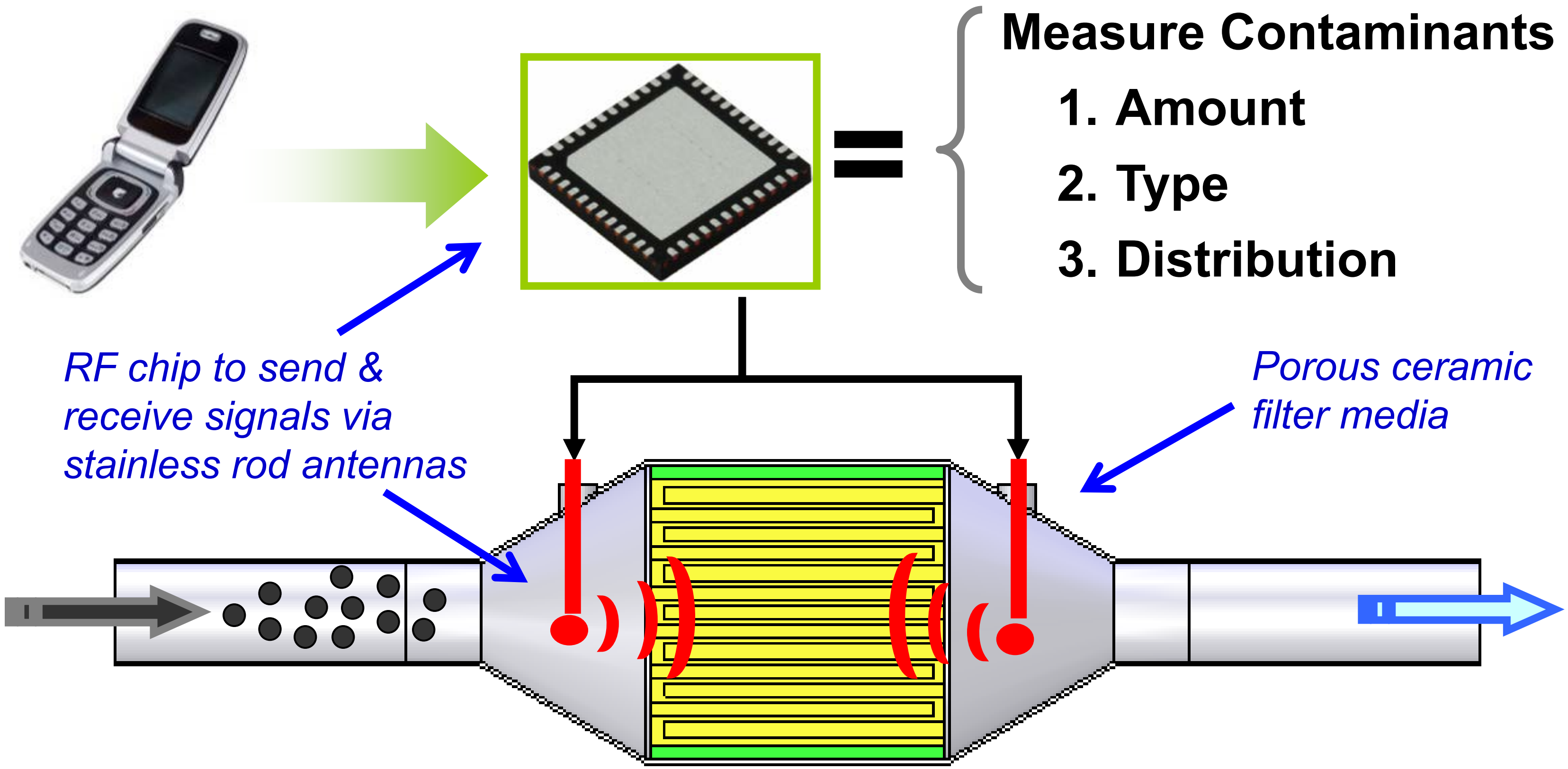
Technical Backup Slides

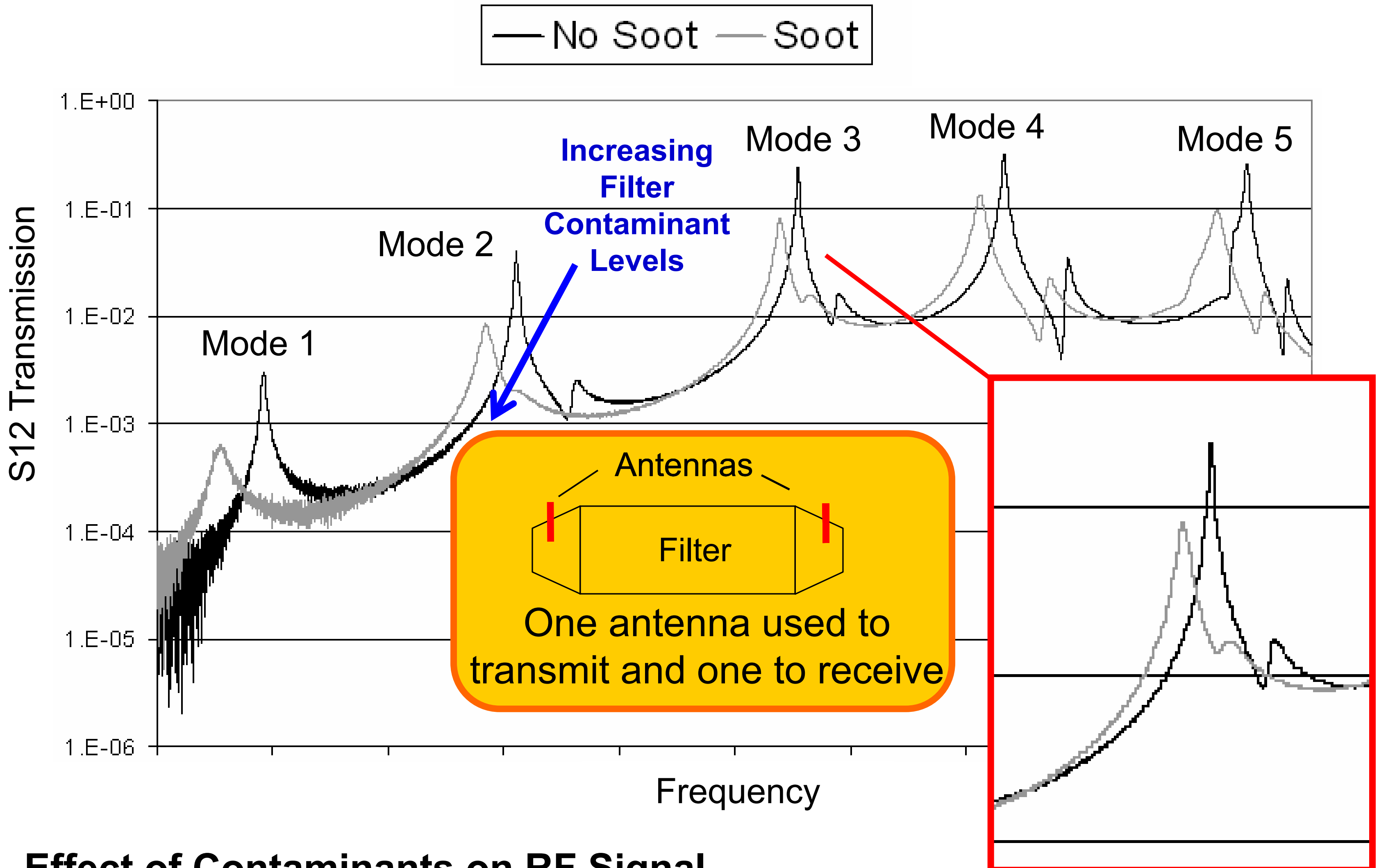
Basic RF Sensor Operation



Opportunities for RF-Based Sensing

- Drop-in measurement system – only stub antennas exposed to flow
- RF electronics based on low-cost wireless chip architecture
- Provides direct measure of contaminants on filter media
- Additional applications and benefits possible with alternative fuels, advanced combustion modes, and for OBD

Example of RF System Operation: Transmission

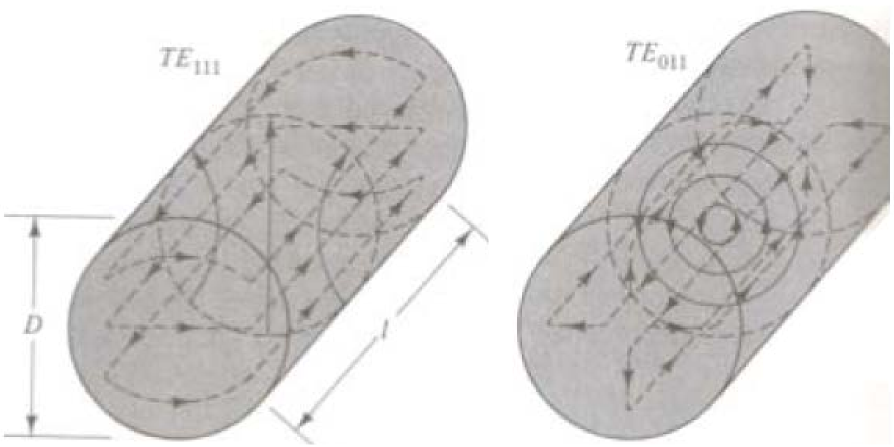


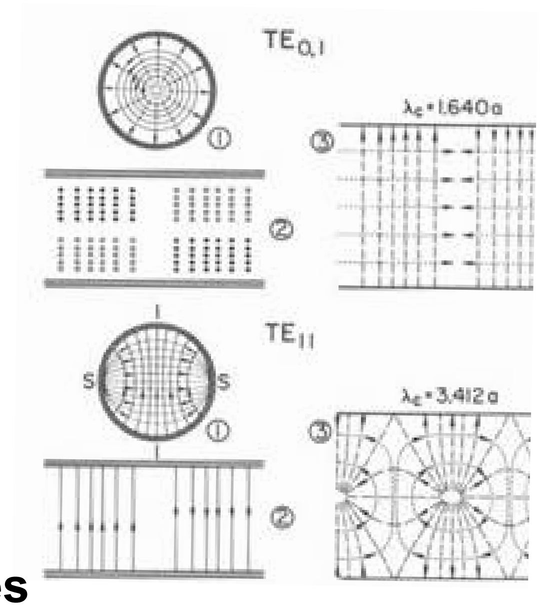
Effect of Contaminants on RF Signal

- Filter resonant modes (peaks) occur at specific frequencies
- Filter contaminant loading affects resonant modes in predictable manner

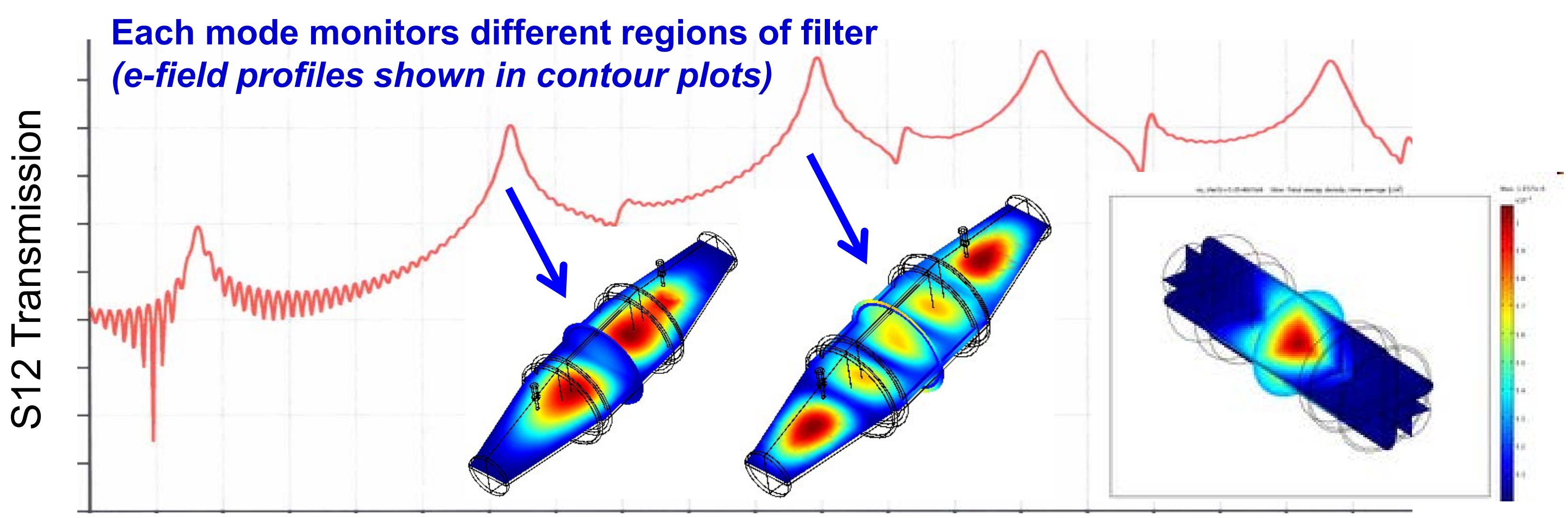
Resonant Modes Also Monitor Spatial Distribution

Typical Resonant Mode Electric Field Profiles*





RF System Models for Filter-Specific Geometries



* Adam, Stephen, F., Microwave Theory and Applications, Prentice Hall, Inc., Engelwood Cliffs, New Jersey, 1969.

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