QUALITY IN ENGINEERING, SCIENCE & TECHNOLOGY

Development of High-Performance Gas-Coupled Ultrasonic Transducers for Inspection of Unpiggable Natural Gas Pipelines

Quest Integrated, LLC

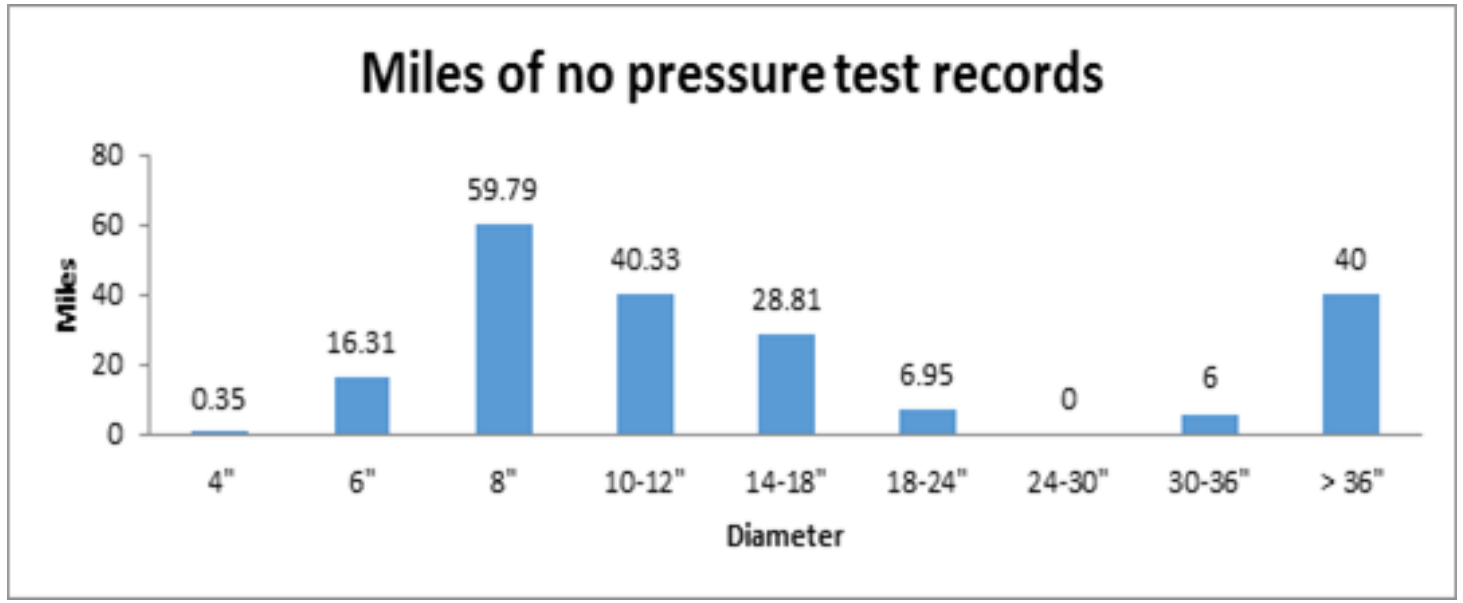
Problem to be Addressed

- Industry has a government-mandated requirement to determine maximum allowable operating pressures and how close the pipeline is to failure. The NTSB has identified in-line inspection (ILI) as preferable to hydrotesting or direct assessment.
- Effective non-contact ultrasonic wall thickness ILI tools for unpiggable gas pipelines have been impossible because excessive mismatch with gas results in almost complete reflection with ~60 dB backwall echo loss for all pipe surfaces plus losses at the transducer and attenuation in the gas.

Material	Z (MRayl)
Natural gas (1 atm)	0.0003
Natural gas (500 psi)	0.0106
Crude oil	1.3
PZT-epoxy composite	9.73-21.8
Solid PZT ceramic	34.2
Steel	39

Problem to be Addressed

- The Gas Technology Institute (GTI) has given specifications for a useful gas-coupled transducer
- The distribution of currently untested lines shows that devices must be capable not only at the relatively high pressures of transmission lines (1,000 psi), but also for smaller, lower pressure distribution lines (250-500 psi).



Project Objective and Methodology

Objective—The project objective is to develop and test bench-scale non-contact gas-coupled single crystal ultrasonic transducers for measuring remaining wall thickness down to 0.25” (6 mm) at a reasonable standoff in traditionally unpiggable or difficult-to-inspect distribution pipelines. Qi2 met this objective in all respects.

Methodology

- **Piezoelectric Material—**Develop single crystal PZT to improve transducer/detector efficiency by up to 3X each direction.
- **Transducer Design—**Use innovative backing and impedance matching materials to improve gas-coupling and reduce ringdown
- **Electronics—**Utilize new electronics design and data analysis techniques to improve signal detection and analysis

Project Funding and Support

Pre-Project Funding 2011-2016

- $1,000,000 Quest Integrated, LLC—laboratory set up and preliminary research
- $120,000 Chevron

Project Period Funding and Support 2016-2019

- $765,995 total funding
- $284,273 PHMSA (including final payment)
- $481,722 Quest Integrated, LLC
- Gas Technology Institute (GTI)—no-cost pressure chamber loan
- Operations Technology Department (OTD)—Technical Advisory Committee

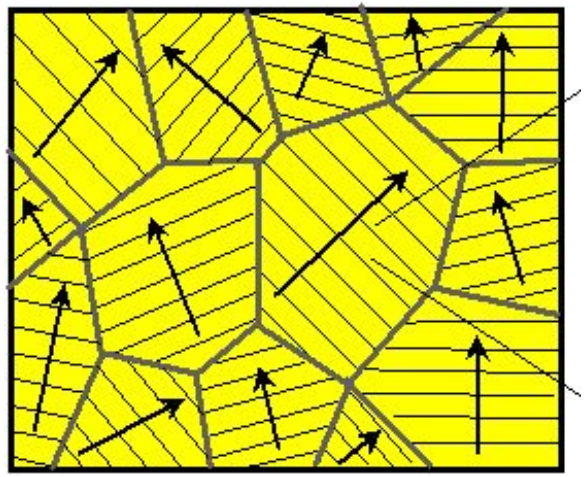
Post-Project Funding 2019-2020

- $2,000,000 Q-Inline milestone payments
- Additional funding being sought

Piezoelectric Technology

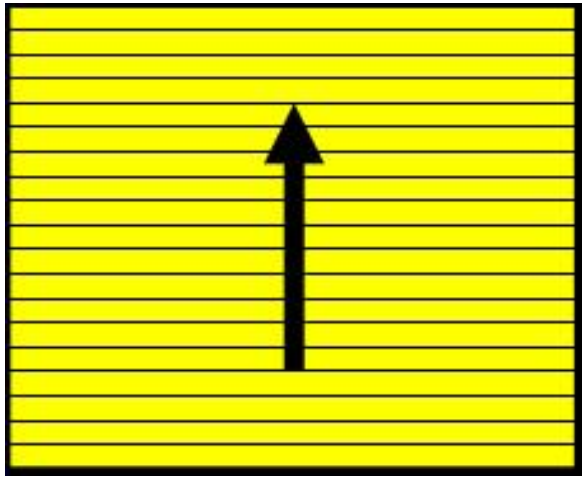
- Lead zirconate titanate (PZT) is the dominant piezoelectric material in non-destructive testing because of its high efficiency and high power capability, but it is only available as a ceramic
- Single crystal PZT can yield 3x efficiency improvement on transduction and detection for ~20 dB system improvement

Ceramics are Incoherent and Omni Directional



Think LED

Single Crystals are Coherent and Directional



Think LASER

Transducer Improvements

Higher Efficiency =

Higher acoustic output power
at a given electrical input power

OR

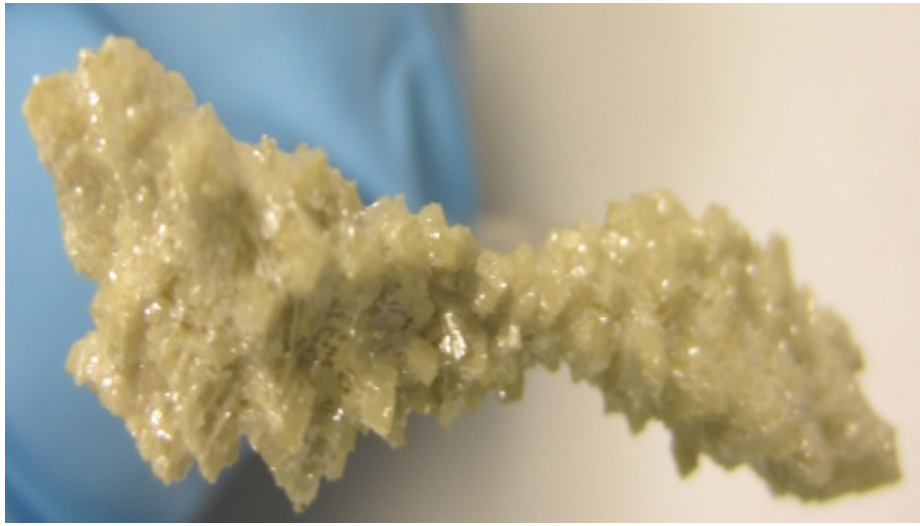
Lower electrical input power
with equal acoustic output power

OR

Smaller size
with equal acoustic output power

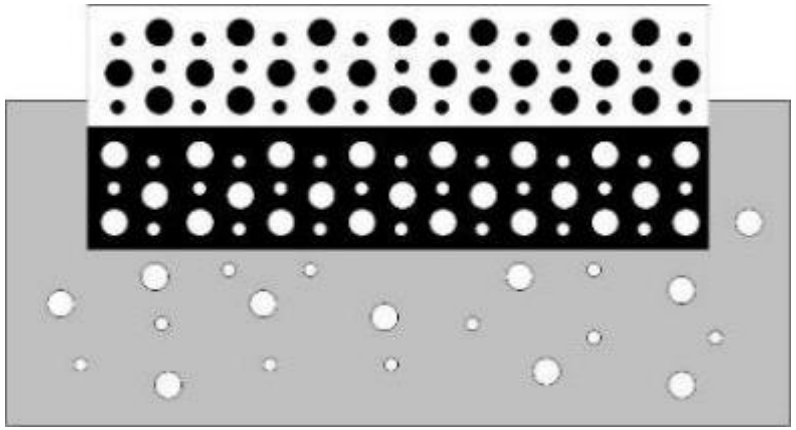
High Temperature Solution Growth

- High Temperature Solution (HTS) Growth has been compared to making rock candy. As much of the desired compound (PZT) as possible is dissolved in a lead oxide-based solvent and then the melt is cooled to precipitate the desired phase.
- Top Seeded Solution Growth (TSSG) allows formation of an initial seed on a dissimilar material (platinum) and using this as the seed for later growth. Crystals were grown > 2 cm^3 meeting all project milestones.



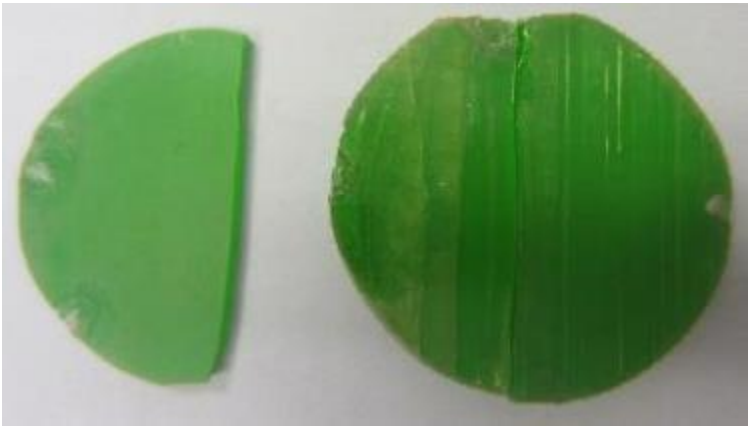
Liquid Phase Epitaxy (LPE)

- Liquid phase epitaxy relies on having a substrate of the same crystal structure and similar lattice parameter to act as a template for the growing crystal.
- Existing substrates experienced cracking problems for thick films
- Invention of new substrate materials turned out to be critical to LPE success
- Substrate implementation issues required postponing this process so the current work used TSSG



Schematic view of LPE

Substrate top Film bottom



Thin uncracked film **Thick cracked film**

Crystal Growth Status

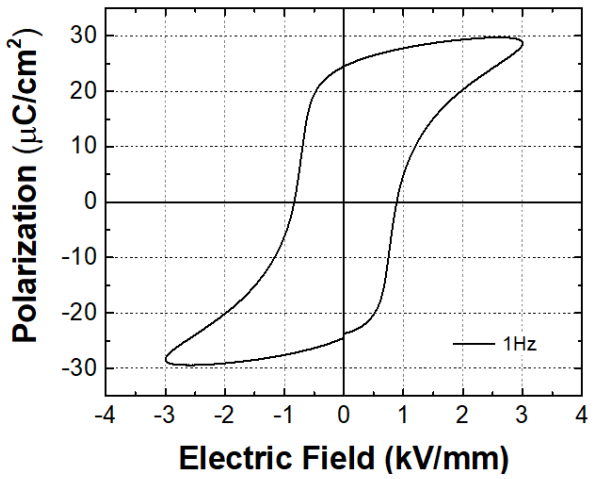
- Qi2 has successfully grown single crystal PZT and demonstrated the path toward commercialization – both firsts, despite 50 years of research effort
- In-house fabrication of crystals was developed
- Patents issued in U.S., China and Japan; pending in Europe
- Improvements underway include
  - Defect reduction through change of flux properties
  - More uniform composition through thermodynamic improvements in solubility
  - increase in size through larger melts
  - Improved substrate materials

Penn State Characterization Results

Results indicate higher output power possible

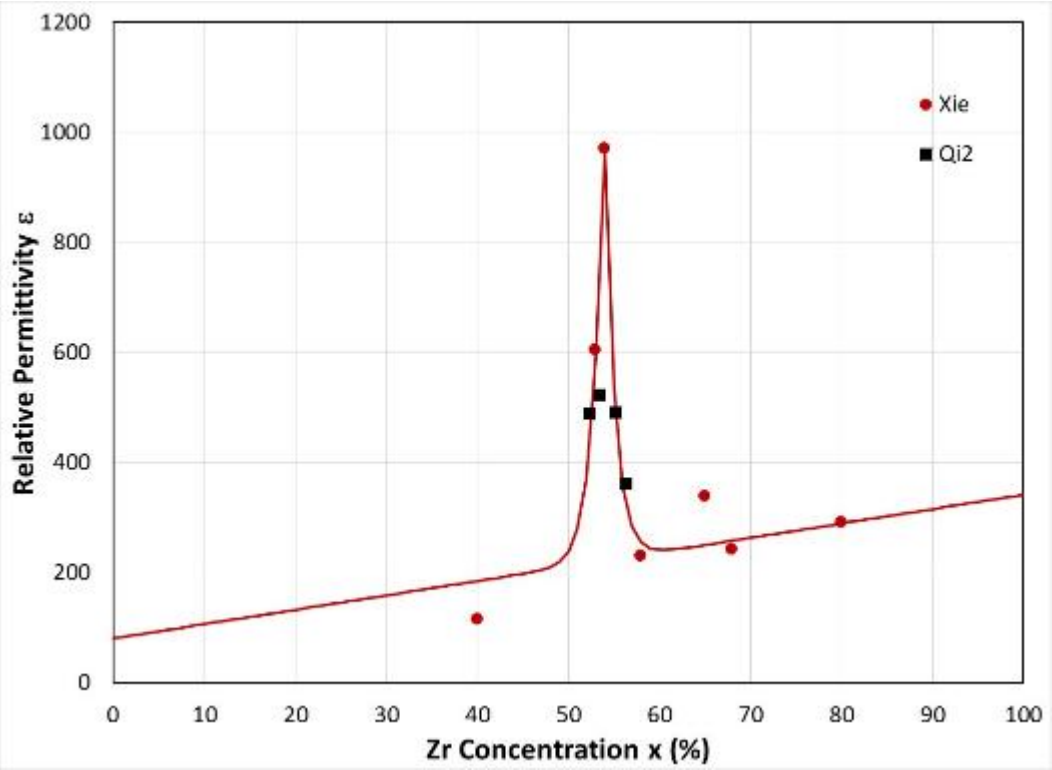
- Polarization-electric field hysteresis and unipolar/bipolar strain loops measured
- Higher d_{33} (power out/voltage in) and k_{33} (coupling) give better efficiency
- Higher coercivity E_C and Curie temperature T_C permit higher power output and operation at higher temperatures without depoling or other damage compared to existing non-PZT single crystals such as PMN-PT

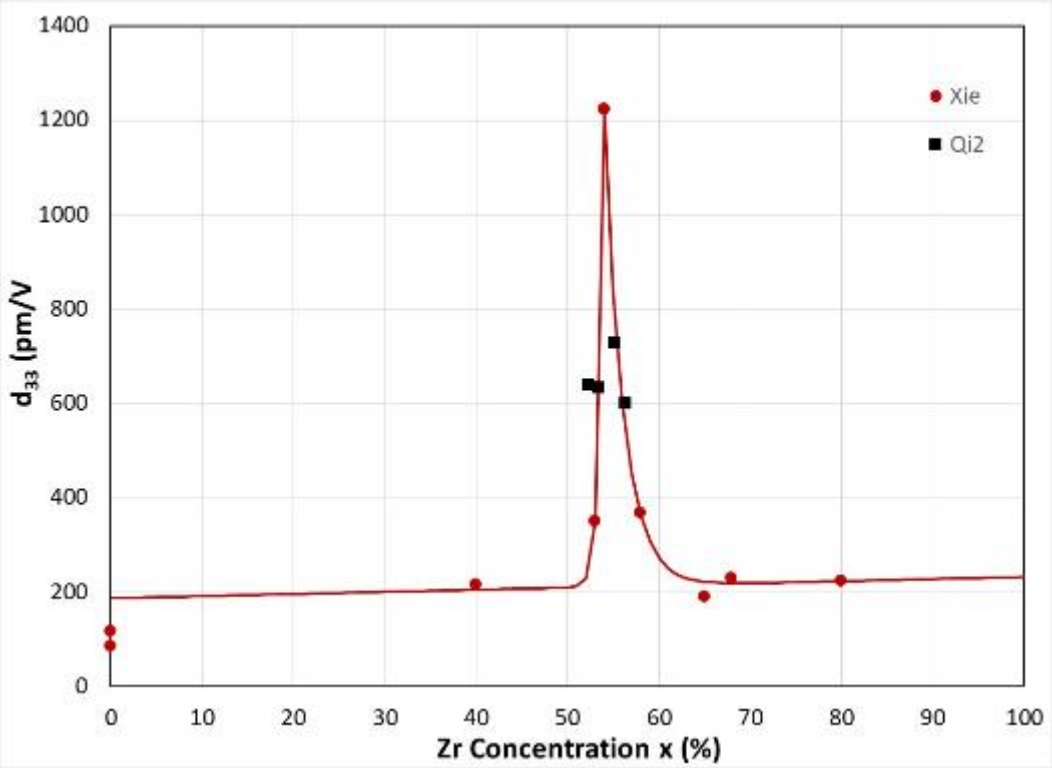
Sample	d_{33}	E_C	k_{33}	T_C
Qi2 large PZT single crystal	727	12.5		401°C
Qi2 projected	1223	12.6	90%	401°C
Navy III hard ceramic	215	15	62%	310°C
Navy VI soft ceramic	630	8	76%	250°C
PMN-PT single crystal	1609	2.5	91%	120°C



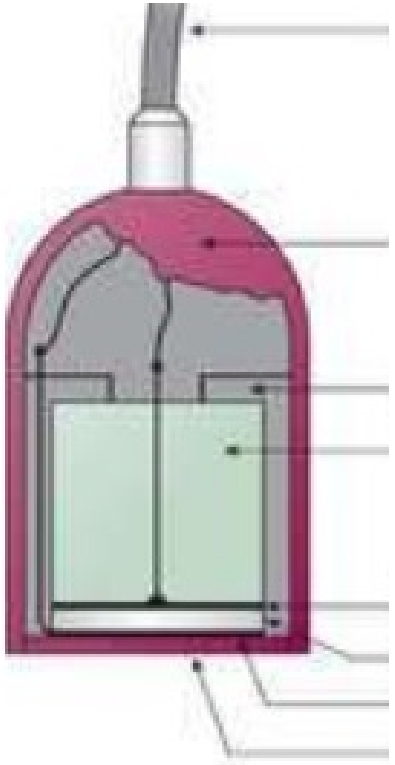
Optimization Based on Results

Relative permittivity ε and efficiency d_{33} show we are near the optimum point, but the narrow peak requires a higher degree of crystal uniformity as is recently being achieved on an ongoing basis





Transducer Redesign



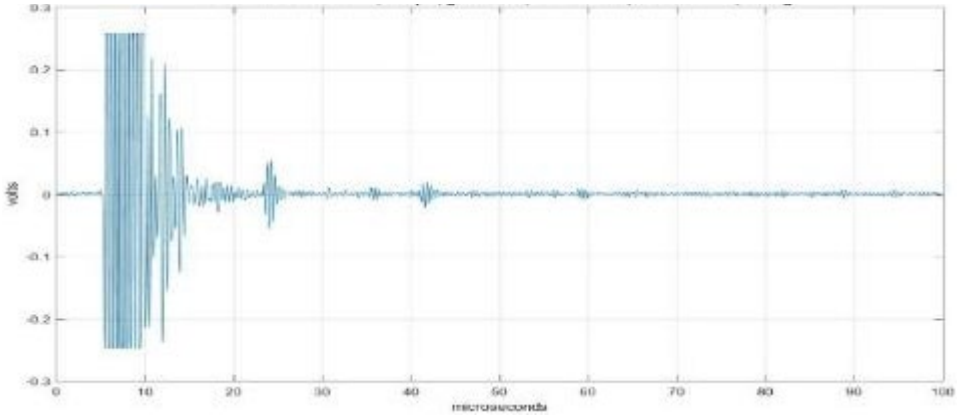
- Computer modeling design optimization program
- LTSpice validation of modeling outputs
- Impedance matching materials redesigned to couple output power and input signal better
- Backing materials redesigned to reduce ringdown
- Feedback with testing
- LTSpice modeling of electronics to get better definition of higher order reflections
- Working with single crystal piezoelectrics
- Patent protection ongoing

Transducer Performance Shows Capability

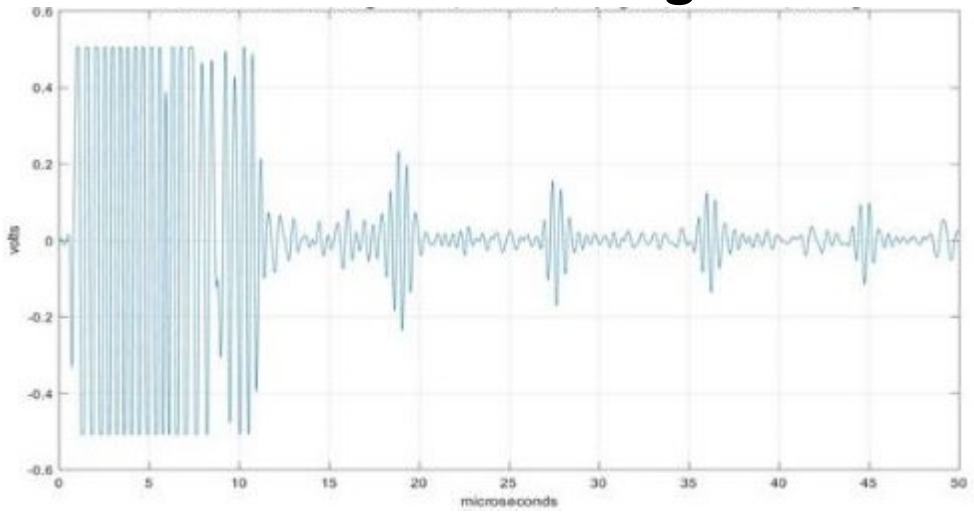
- Substantial improvement over prior art transducers
- Results on thick sample show multiple back wall reflections
- Improvement in ringdown designed into next iterations

	1st Surface Echo Amplitude	Ringdown (µs)	Backwall Echo Amplitude
Prior art	0.020	5.6	0.00001
#187	0.023	13.8	0.00003
#188	0.021	11	0.00004

Prior art

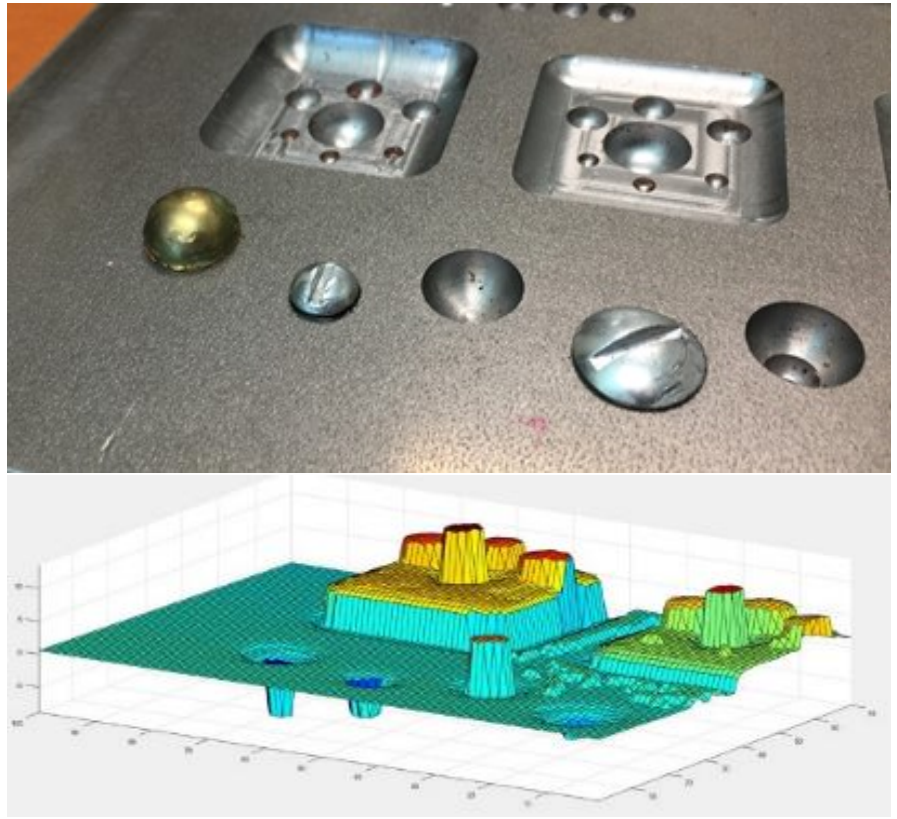


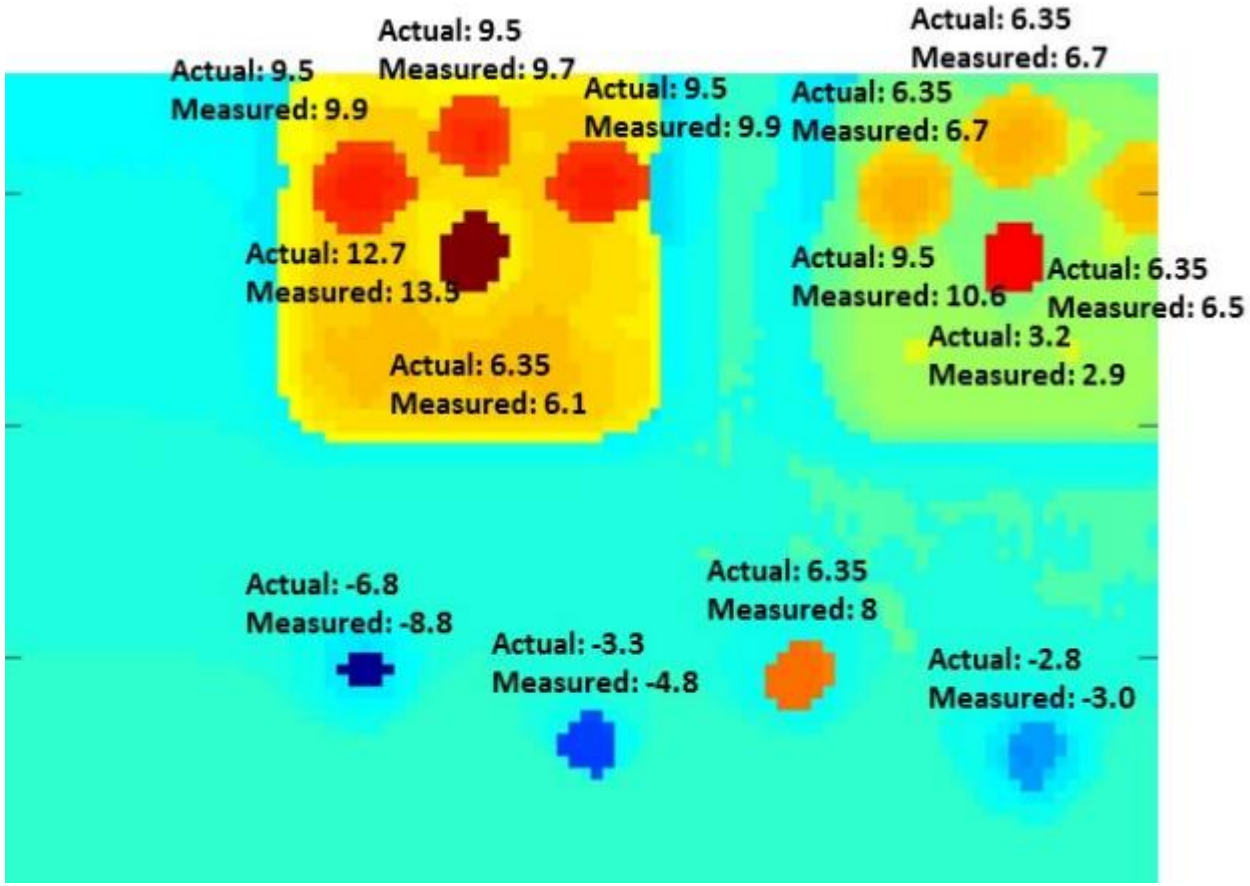
Current Design



Caliper Inline Inspection Tool

- Front surface results are so strong that surface profiling is possible at 1 atmosphere
- Potential for immediate commercialization



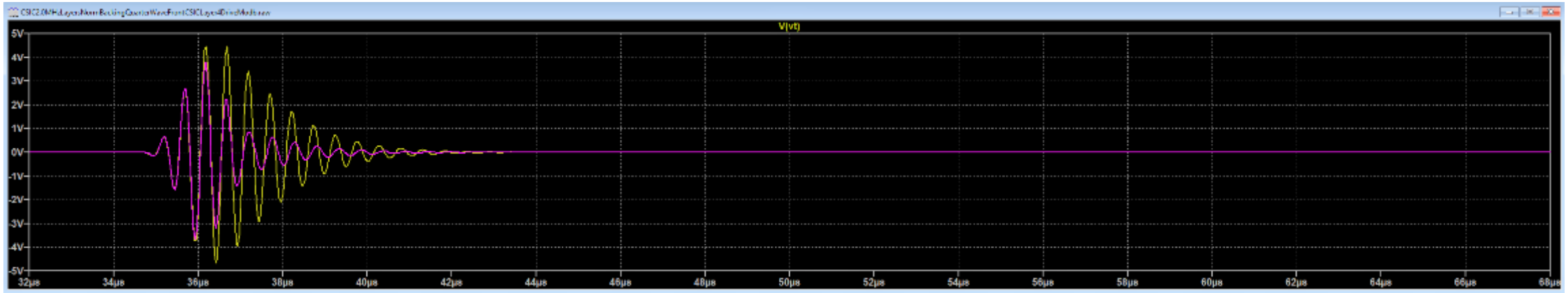


Electronics Innovations

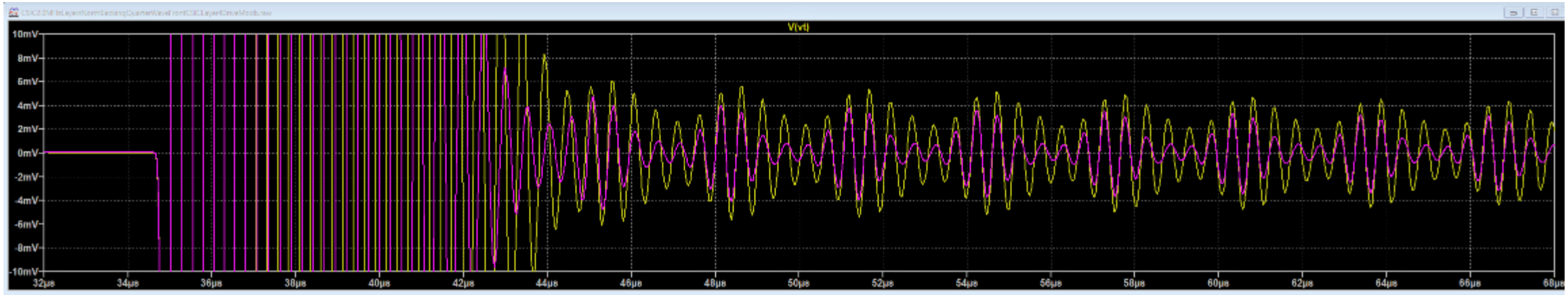
- Electronics development has been synergistic with other projects at Qi2
- The electronics improvements that came out of the modeling activity were used with the sensors developed in this project to achieve the milestone results.
- Coupled with the newly developed transducers, the system is effective in producing an accurate thickness measurement down to 6 mm with 0.05mm accuracy at a 1” standoff and 250 psi.
- Current electronics and data analysis innovations remain confidential until patent protection is in place
- Additionally, Qi2 has been working on miniaturization of electronics to permit a much shorter tool with much of the data analysis on board to reduce storage requirements

Modeling of Electronics Innovations

Front Surface—Green is standard electronics, purple is innovation

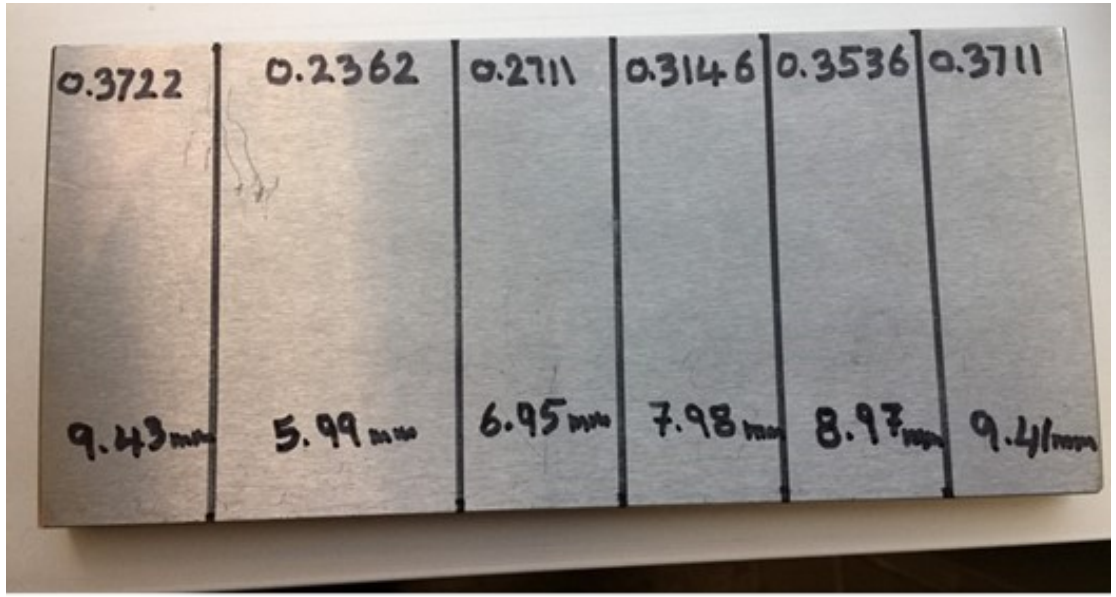


Amplified to see Back Surface Reflections



Pressure Test Chamber on Loan from GTI

Stepped Sample for Final Testing

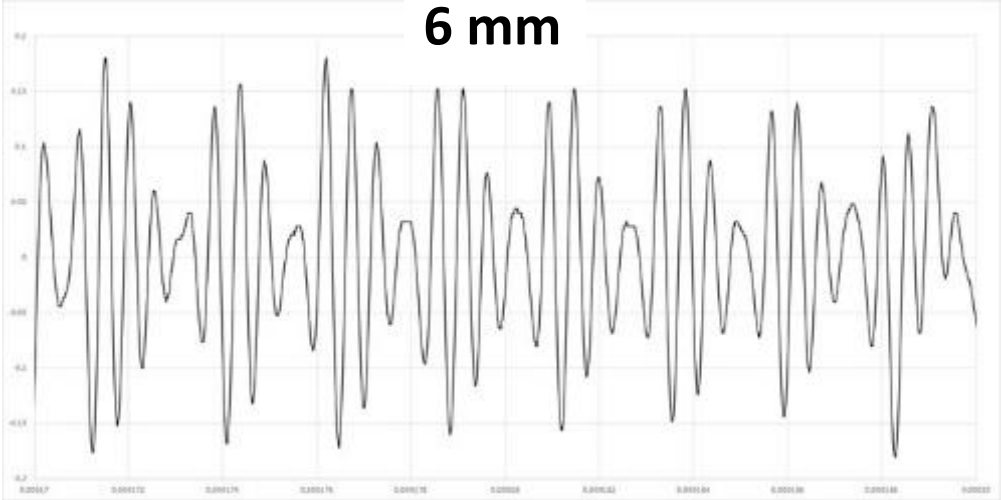


Measurement of Stepped Steel Plate at 250 psi

Meets all objectives!

- Benchtop demonstration
- 6 mm thickness
- 250 psi
- 1” standoff
- < 0.05 mm error

Gas-coupled ultrasonic transducers suitable for wall thickness measurements feasible for the first time



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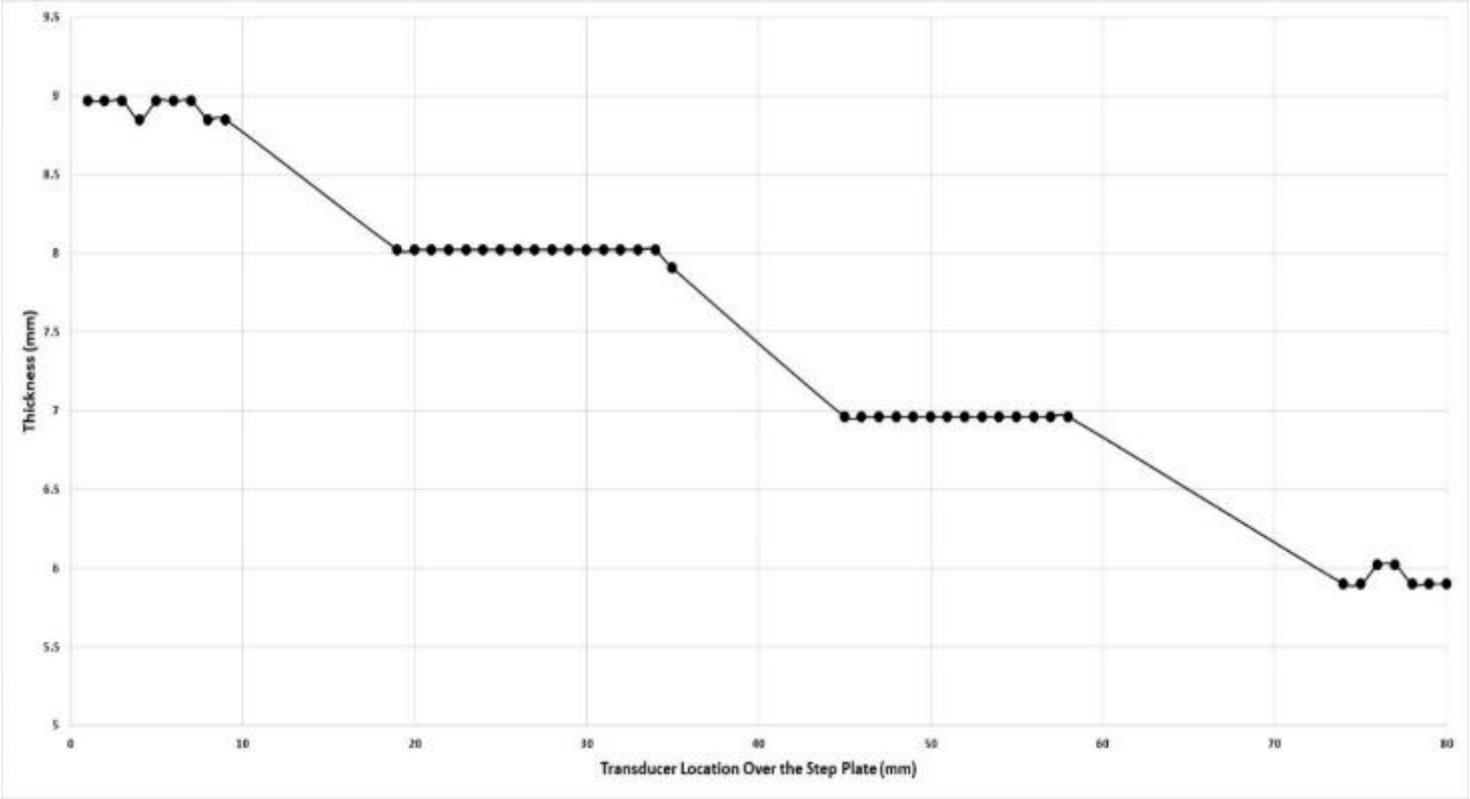

Nominal Thickness	9 mm step	8 mm step	7 mm step	6 mm step
Micrometer Measured Thickness	8.97 mm	7.98 mm	6.95 mm	5.99 mm
Gas-Coupled UT Measured Thickness	8.93 mm	7.97 mm	6.99 mm	5.96 mm

Project Timeline and Obstacles

Project timeline expanded from 2 to 3 years with two extensions because of issues found during the project, but eventually all milestones were met

Issues that caused delays

- Crystal growth method changed from LPE to TSSG
- External crystal fabrication ineffective so process was taken in-house
- Defect density in crystals needed to be improved for Penn State measurements
- Penn State workload required extra time for measurements
- Transducer assembly outsourced with additional $50,000 subcontract
- Transducer ringdown needed to be improved with an additional iteration

Technology Transfer Plans

Qi2 is partnering with Q-Inline (Quanta Inline Devices), a company of Quanta Services (NYSE: PWR), to bring a suite of new gas pipeline ILI tools to market including EMAT crack, EMAT wall loss and gas-coupled UT wall loss. The following is a tentative timeline for the UT wall thickness tool:

- Successful capability testing for Q-Inline complete in 2019
- Jan-Sept 2020 seeking funding
- Sept 2020-Sept 2021 build prototype
- Sept 2021-March 2022 test prototype
- March 2022-March 2023 build first commercial tool
- April 2023 first service offering

Thank You!

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Final Public Report and this presentation available at

https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=724