Mechanical Characterization of Fuel Injector Piezoactuators and Their Piezoceramics

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The Following Will Be Presented

- **Background**
  - **Goals**
  - **Why piezo multilayer actuators (MLAs) for fuel injectors?**
- **Testing (Micro and Macro)**
  - **Piezoceramic - effect of E field on mechanical strength**
  - **Piezoactuator - changes in displacement and strain**
- **Summary**
- **Future work**

Several Motivations Drive This Project

- **HVPM Program seeks more precise spray control of fuel injectors - MLAs an enabler**
- **Piezo MLAs can reduce NO_x, particulates, fuel consumption, and engine noise**
- **At issue - PZT actuators susceptible to electromechanical fatigue and are brittle; adapt structural ceramic design methods**
- **Evaluate MLA reliability under representative service conditions**
- **Link constituent micromechanical and MLA macromechanical responses**

Piezo-actuated fuel injector used in Ford 6.4L Power Stroke® diesel engine

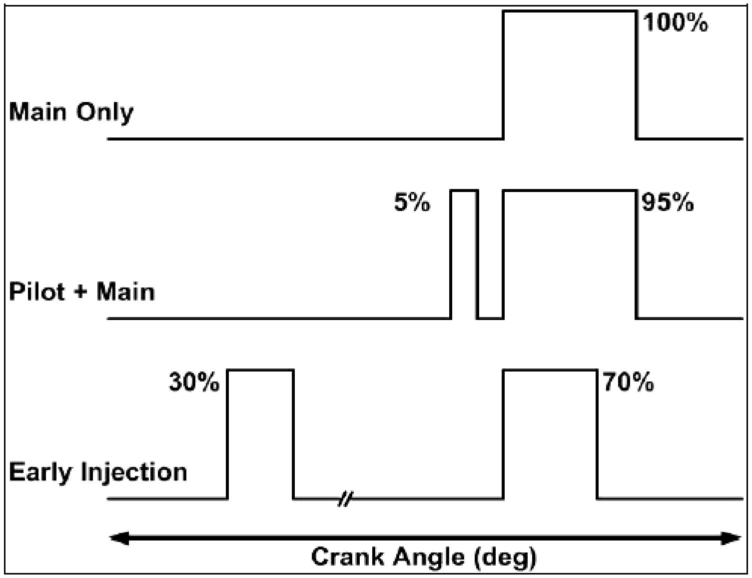
Piezoactuation in Fuel Injectors Has Advantages

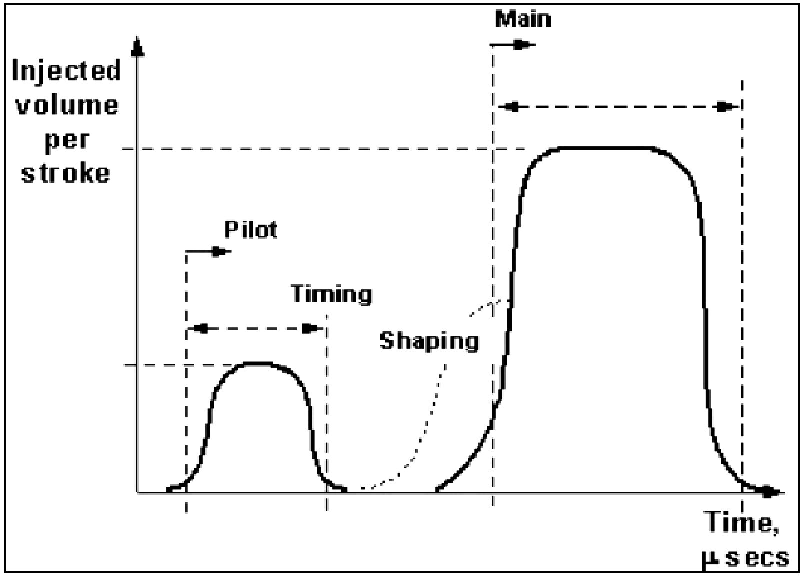
Solenoid actuation

- **Limited to binary response**
- **Controls fuel quantity well but limits flow rate profile control**

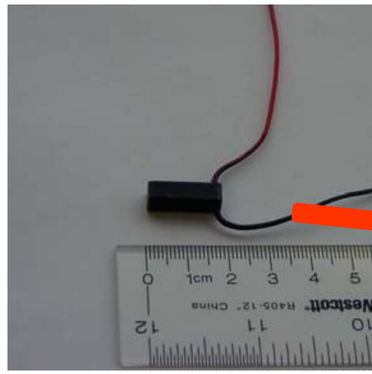
Piezo actuation

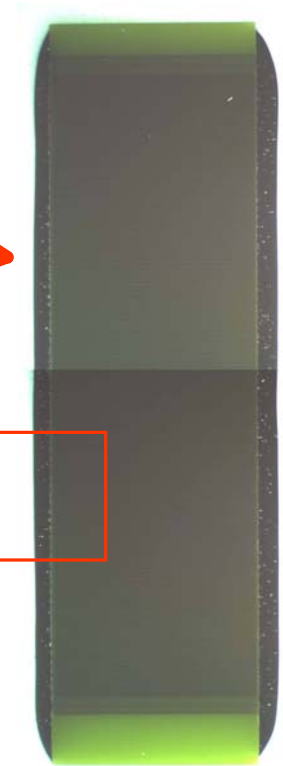
- **Enables rate shaping**
- **Controls both injection timing and fuel quantity control**

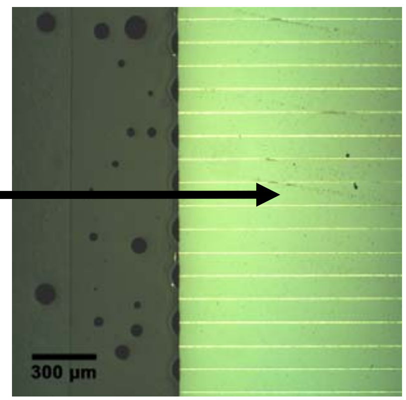




Piezoceramic Characterization: Part 1 of 2



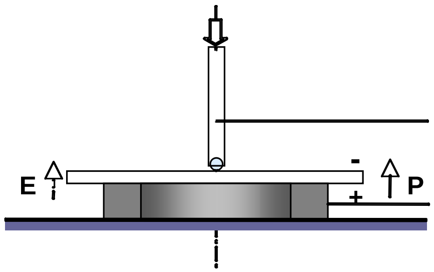


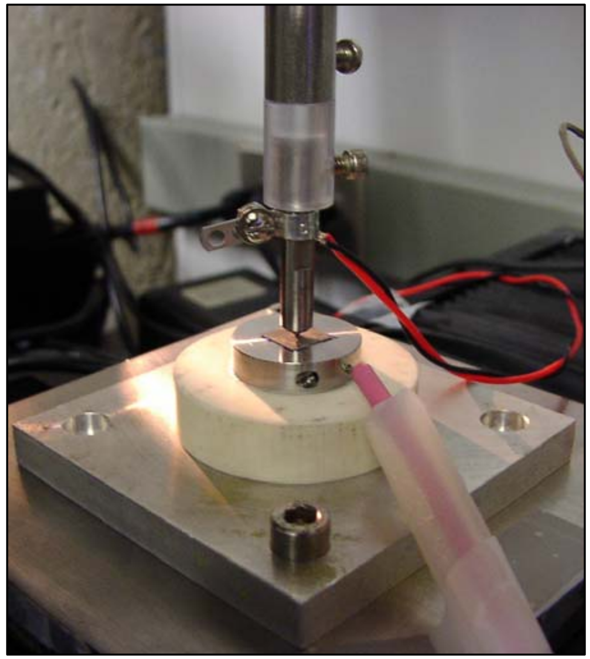


Testing of stand-alone PZT layers

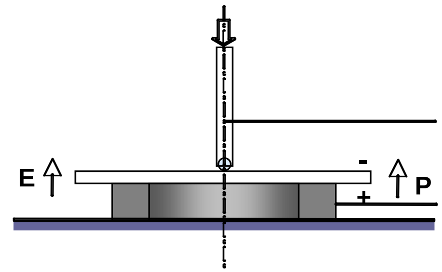
Effect of E Field on Mechanical Strength (4 Cases)

[1] Open circuit & "+" electrode in tension

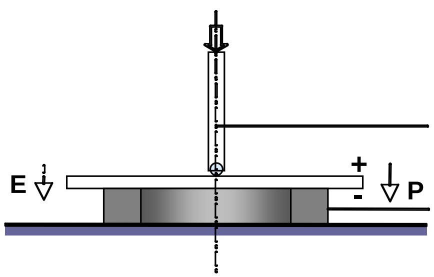




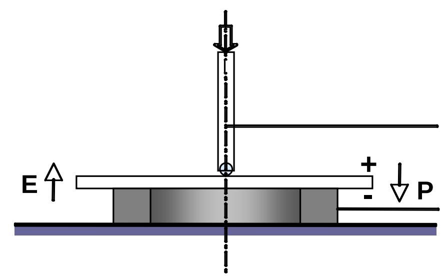
[2] Electric field & "+" electrode in tension



[3] Open circuit & "-" electrode in tension

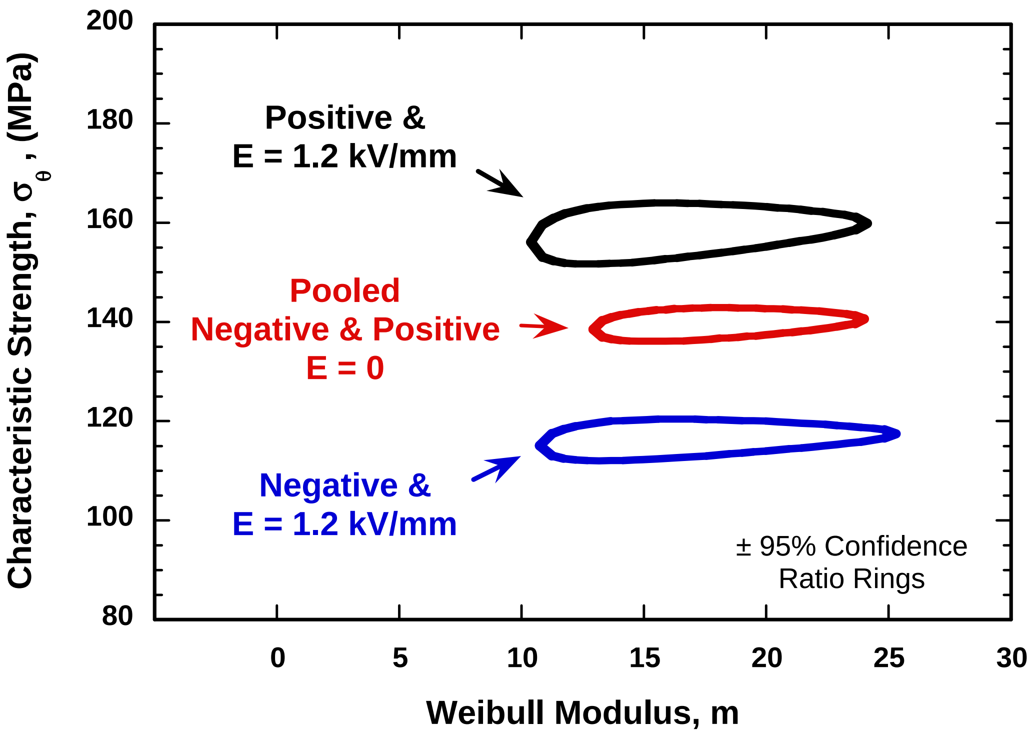


[4] Electric field & "-" electrode in tension

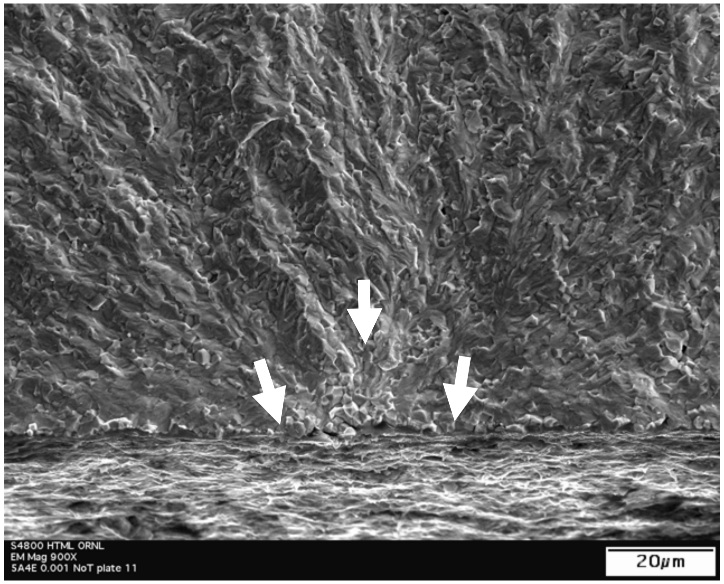


Ball-on-ring configuration, 2 mm steel ball diameter, steel supporting ring 7.4 mm ID, specimen = 10 x 10 x 0.273 mm, applied voltage 327 V or $E_{applied} = E_c = 1.2$ kV/mm

Electric Field Affects Mechanical Strength

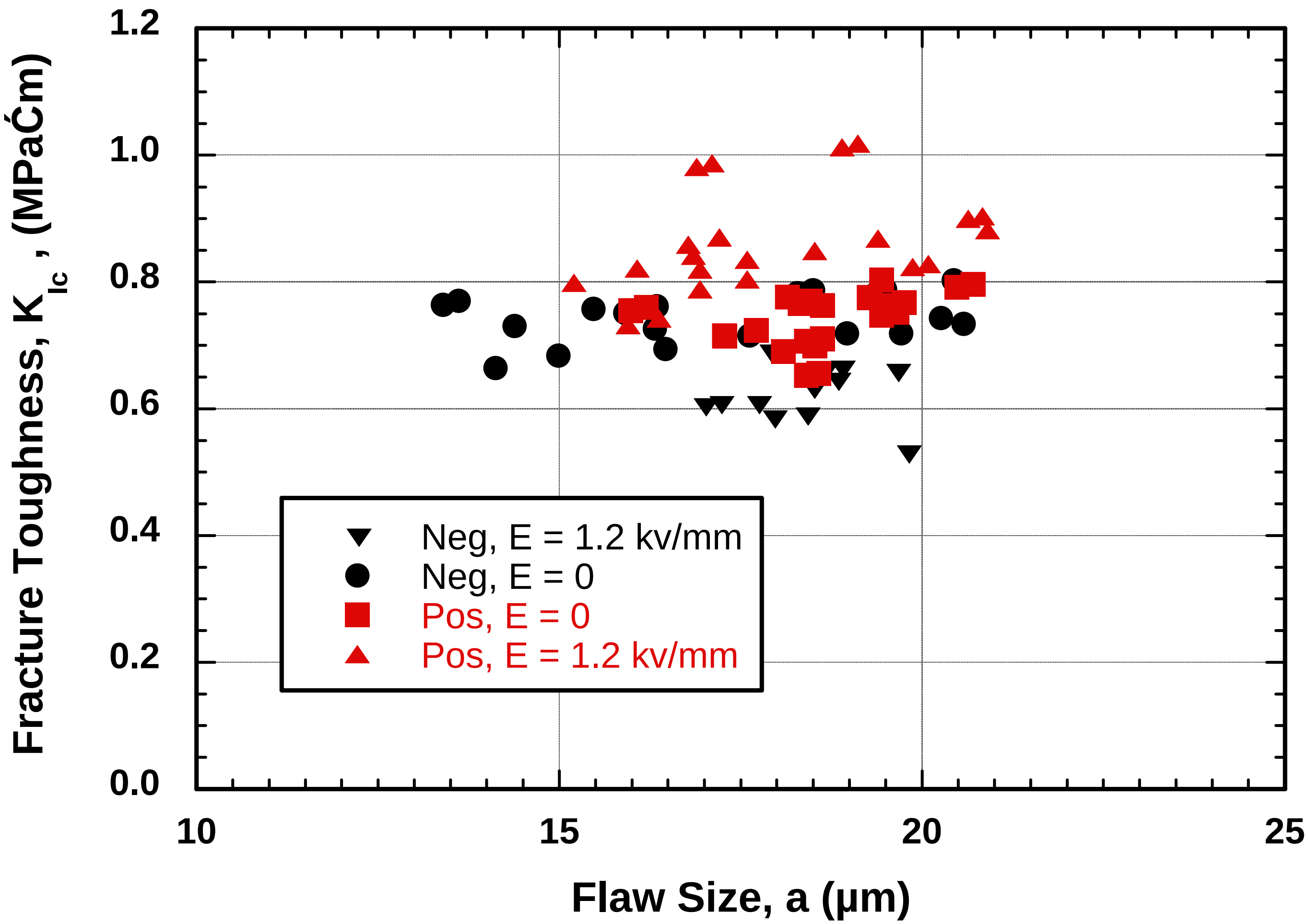


Surface-located defects were the strength-limiters

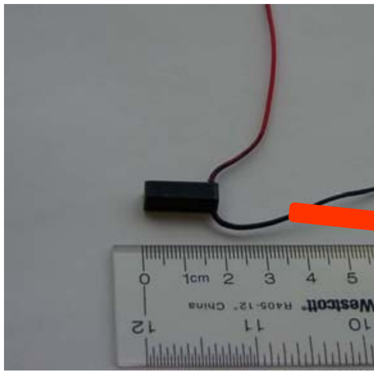


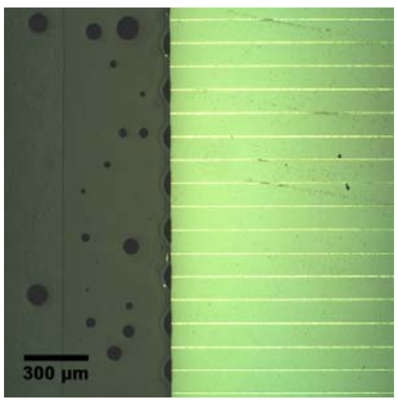
Porous Region

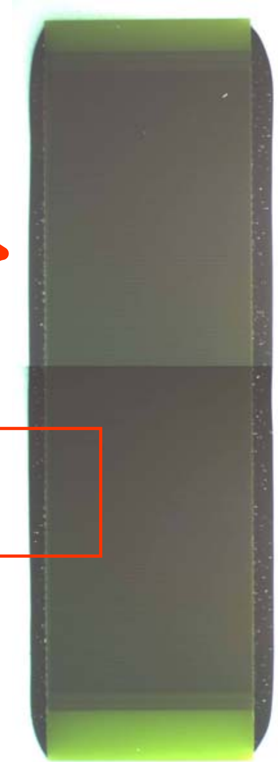
Fracture Toughness Dependence on E Field



Piezoactuator Characterization: Part 2 of 2



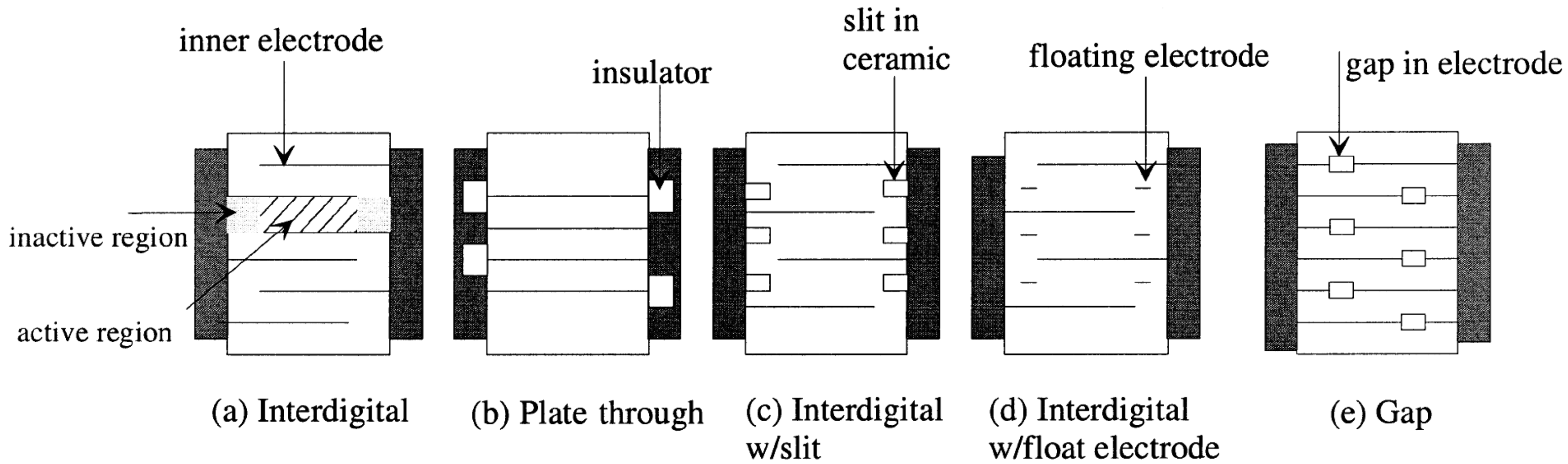




Testing of entire MLA

Evaluation of a "Plate-Through" MLA

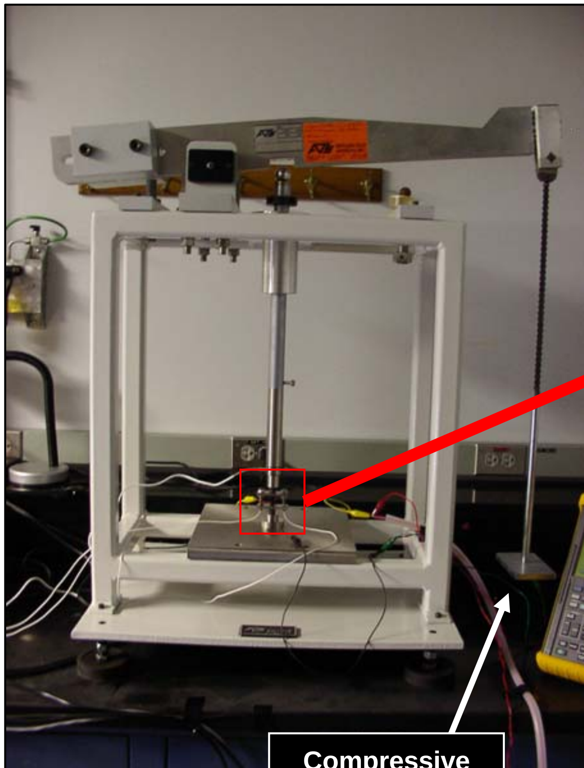
- **Configuration (a) is most common but stress concentrations result from discontinuities at ends of electrodes**
- **Configurations (b)-(e) proposed to resolve stress concentration issue**

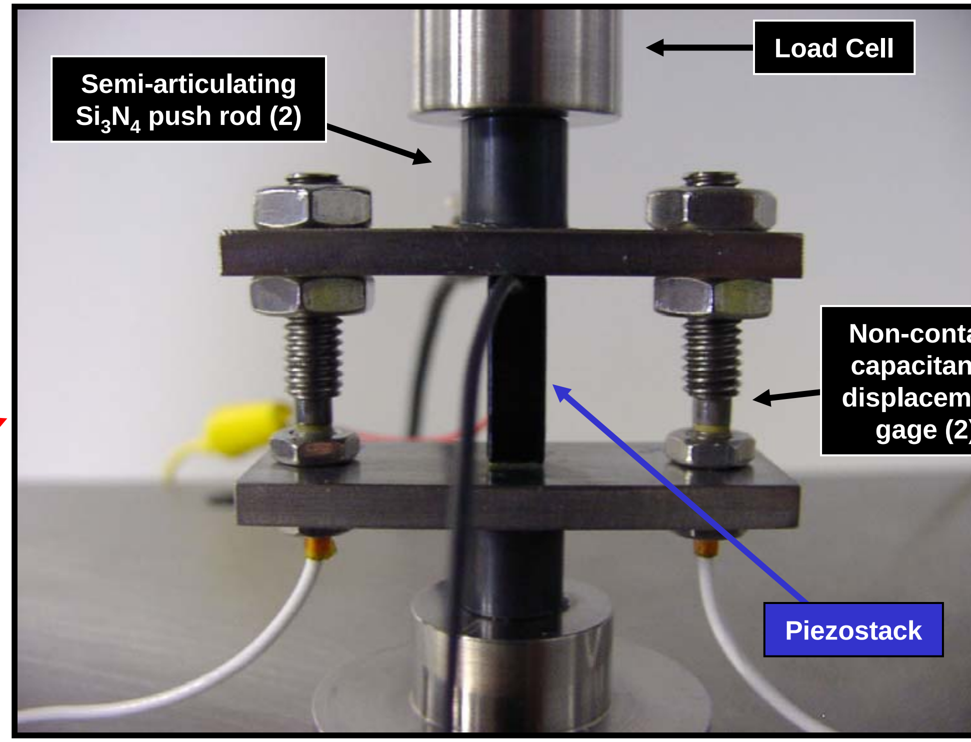


(Aburatani et al., 1994; Pritchard et al., 2001)

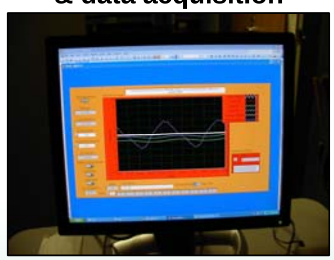
ORNL Piezoactuator Mechanical Test Facility

Piezoactuator Test Frame



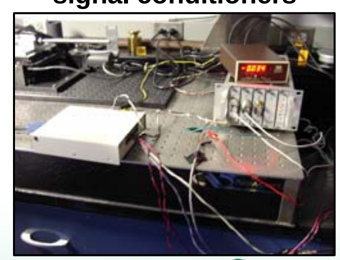


Labview test control & data acquisition



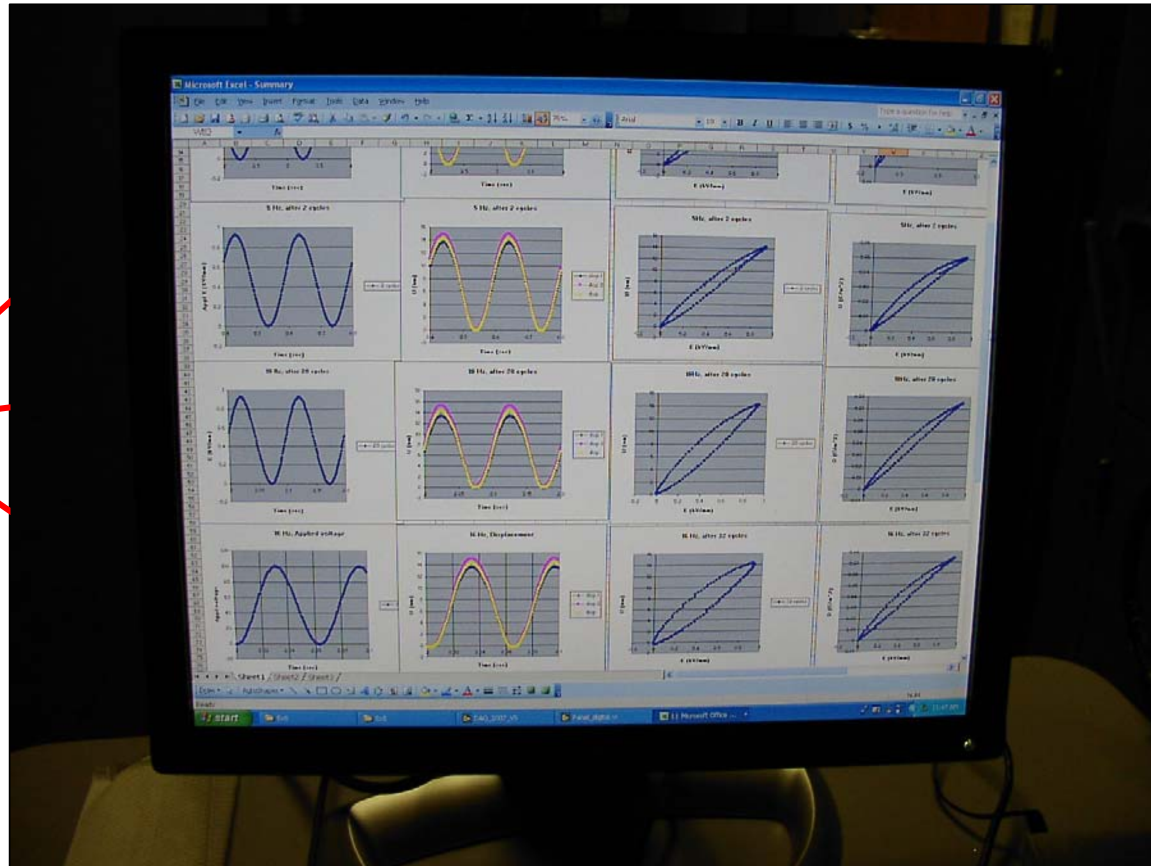
High voltage & high frequency amplifiers

Load and displacement signal conditioners



Special Software Enables Test Control, Parameter Monitoring, and Data Acquisition

Different Frequencies

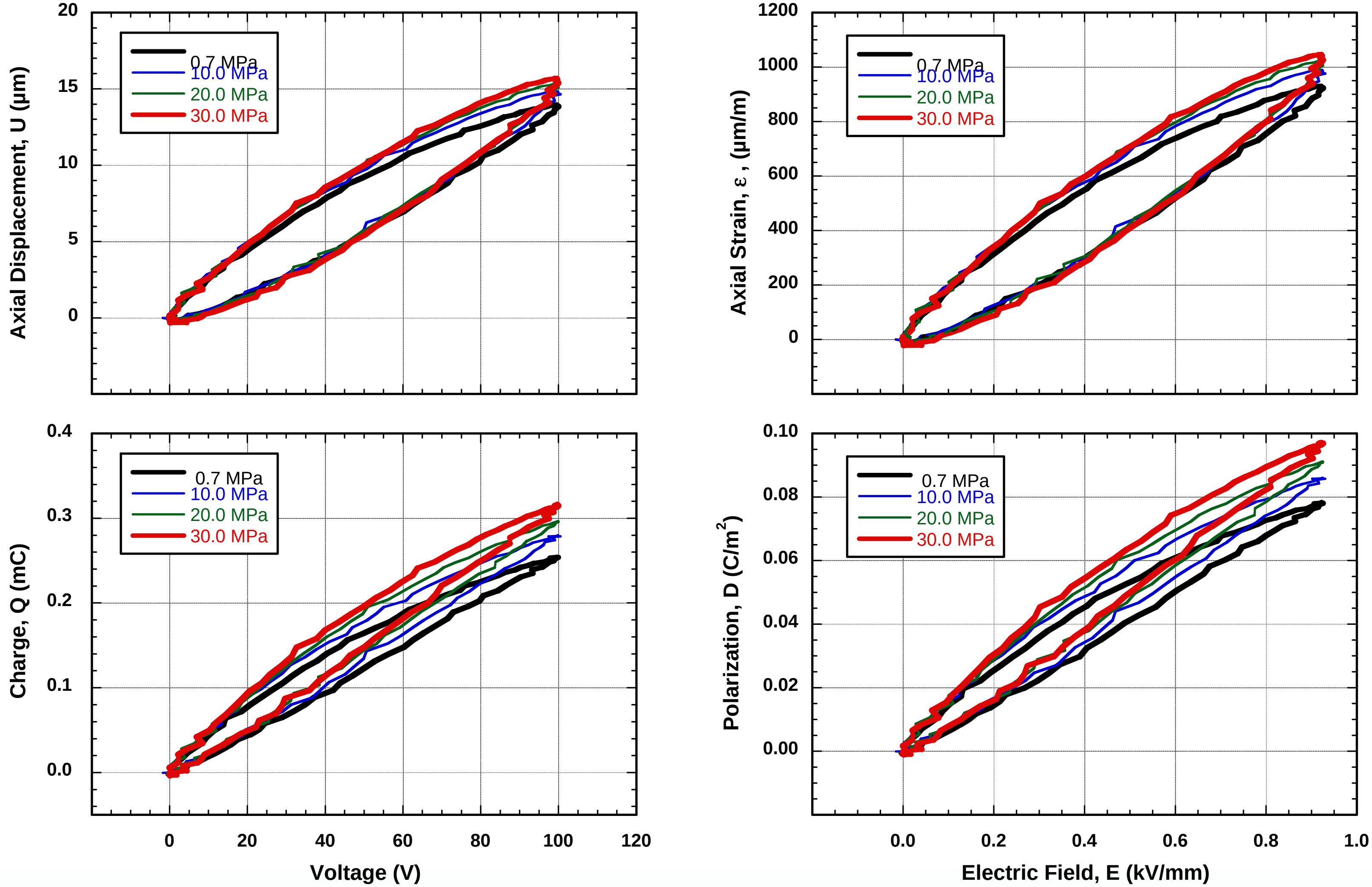


***f* (time)**

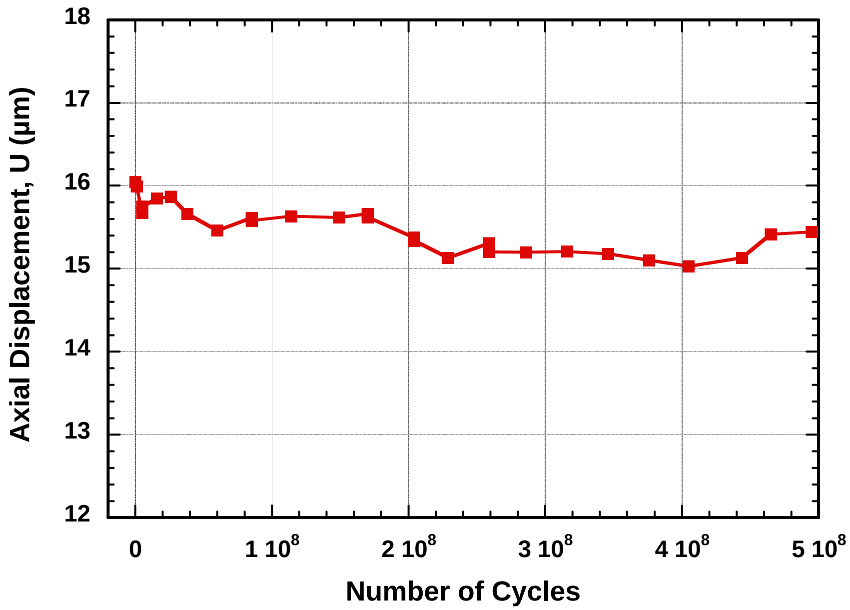
as a
***f* (time)**

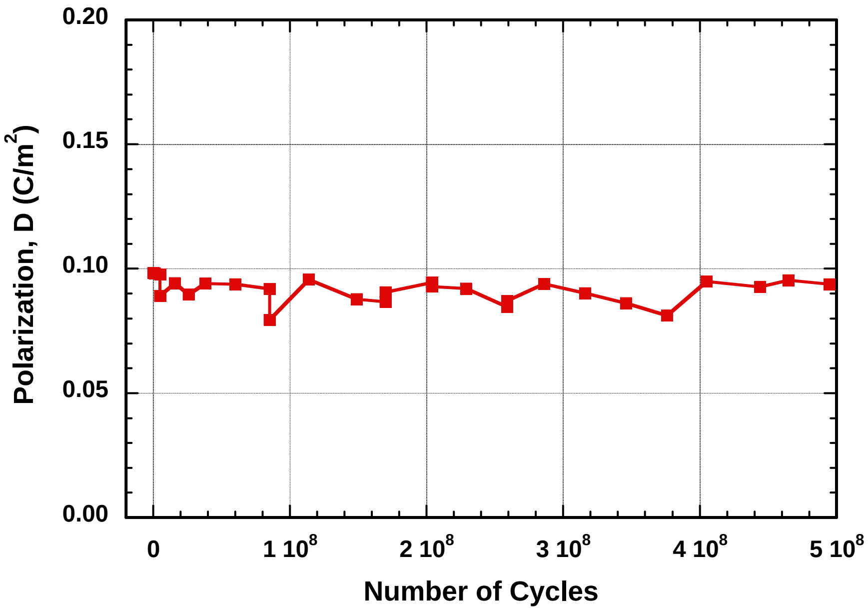
ensity
(E)

Static Compressive Stress Affects MLA Response



~ 5% Decrease in Actuator Displacement Response But Polarization Unchanged



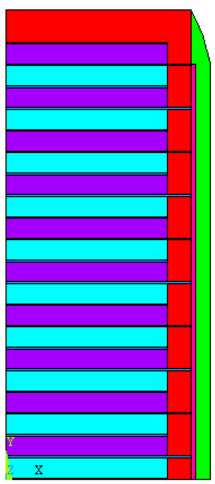


$5\ 10^8$ cycles ~ 115 days

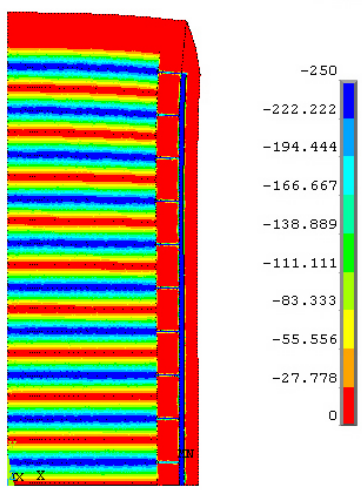
Test condition: unipolar sine waveform with 150V amplitude, 50 Hz, and 30 MPa static compressive stress

FEA & PDS of MLA Enables Reliability Prediction and Design Optimization

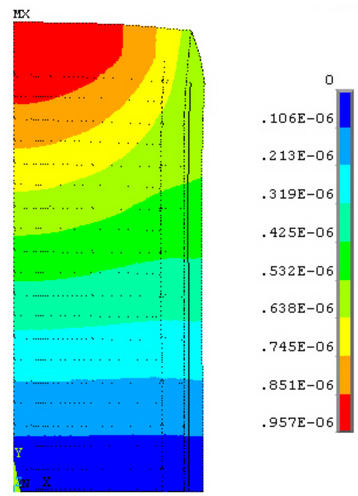
1/4 Model of MLA



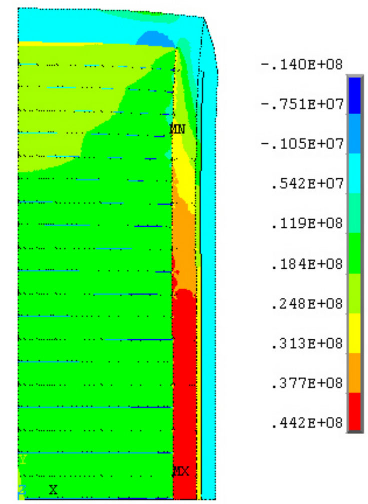
Applied Voltage



Axial Displacements



1st Principal Stresses



Ceramic reliability limited by tensile S1

Summary

- **Mechanical test facilities established to enable evaluation of both**
  - **Piezoceramics (microstructure)**
  - **Piezoactuators (macrostructure)**
- **Strength of poled PZT is side dependent with negative side weaker in tension. Surface-located flaws were strength-limiters.**
- **~ 5% strain reduction observed during 500M cycles in a PZT MLA with no significant loss of polarization. (30 MPa static compression and unipolar waveform at 150V and 50Hz)**
- **Reliability of piezoactuators is affected by microstructural and macrostructural flaws and damage.**
- **Displacement reduction may be due to pinned domain motion.**

Future Work and Pursuits

- Actively pursue collaborations with both MLA manufacturers and end users
- Fabricate additional MLA fatigue test frames
- Add environmental testing capability
- Add piezoactuator to load train(s)
- Monitor MLA self-heating
- Add mixed loading capability
- More in-depth FEA and PDS commencement