Forum on Tracking Detector Mechanics 2023

Estimation of Interfacial Strain Response for a Bi-material Strip in Tensile and Shear Loading Using THz-TDS

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Presentation flow

1 Introduction

2 Experimental and theoretical approach

3 Experimental measurements

4 Results and discussion

5 Derivation for correlating ΔToA to volumetric strain for a tension test (back up slides)

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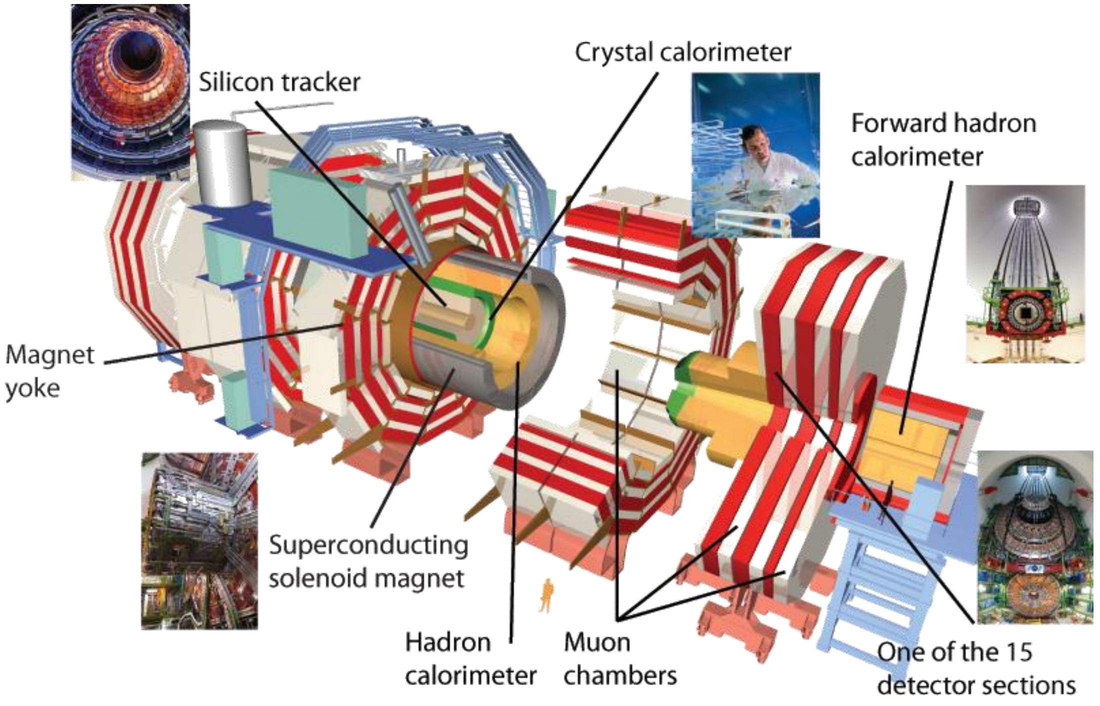
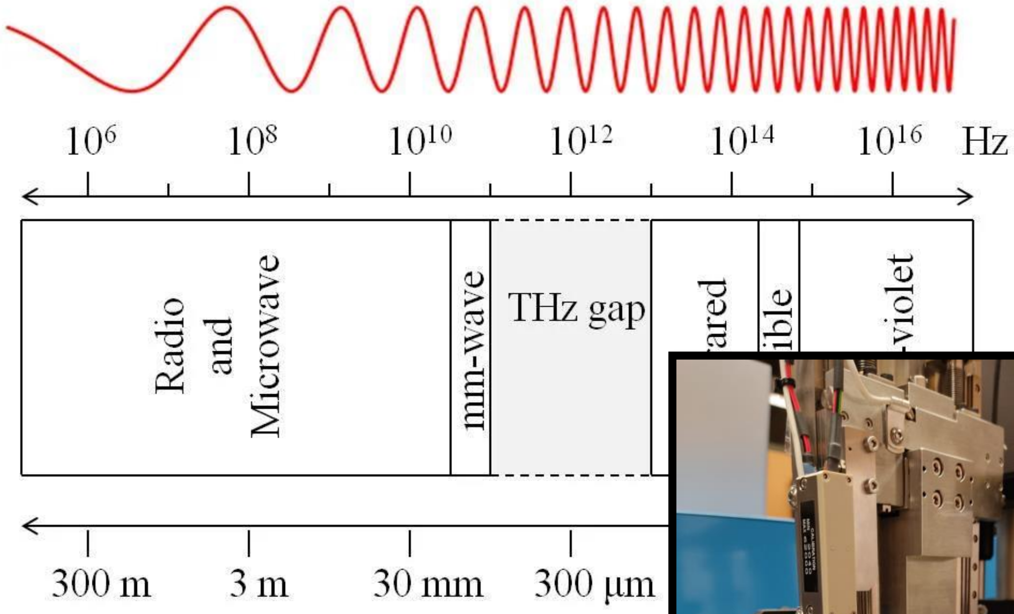
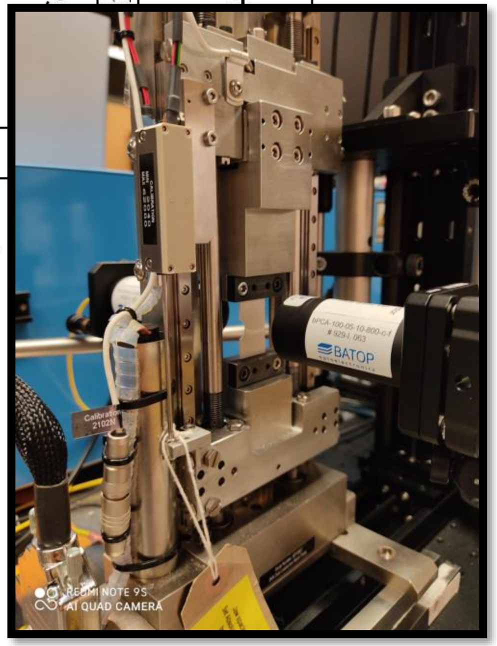
1. Introduction



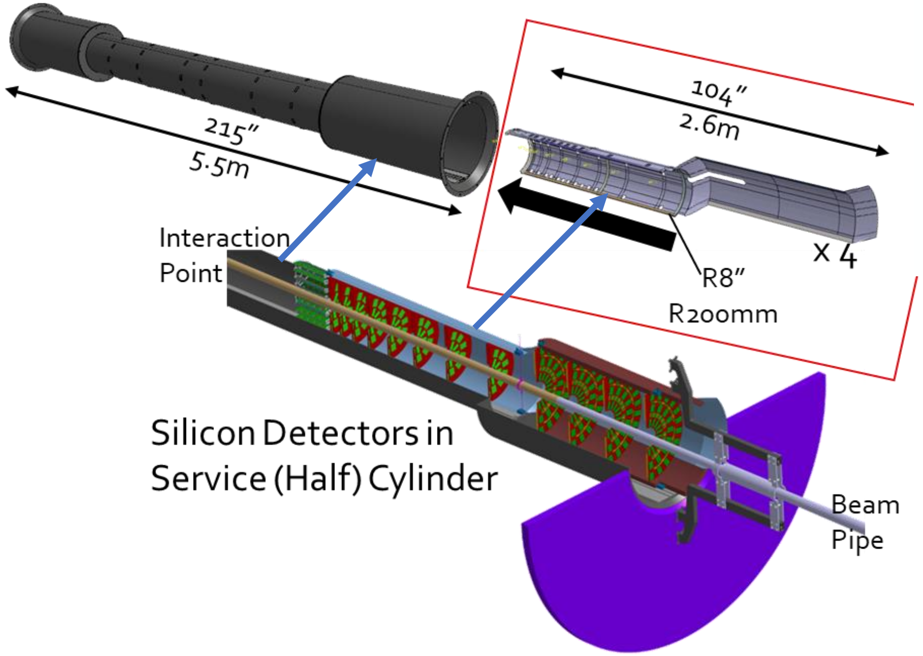
Compact Muon Solenoid detector at LHC-CERN

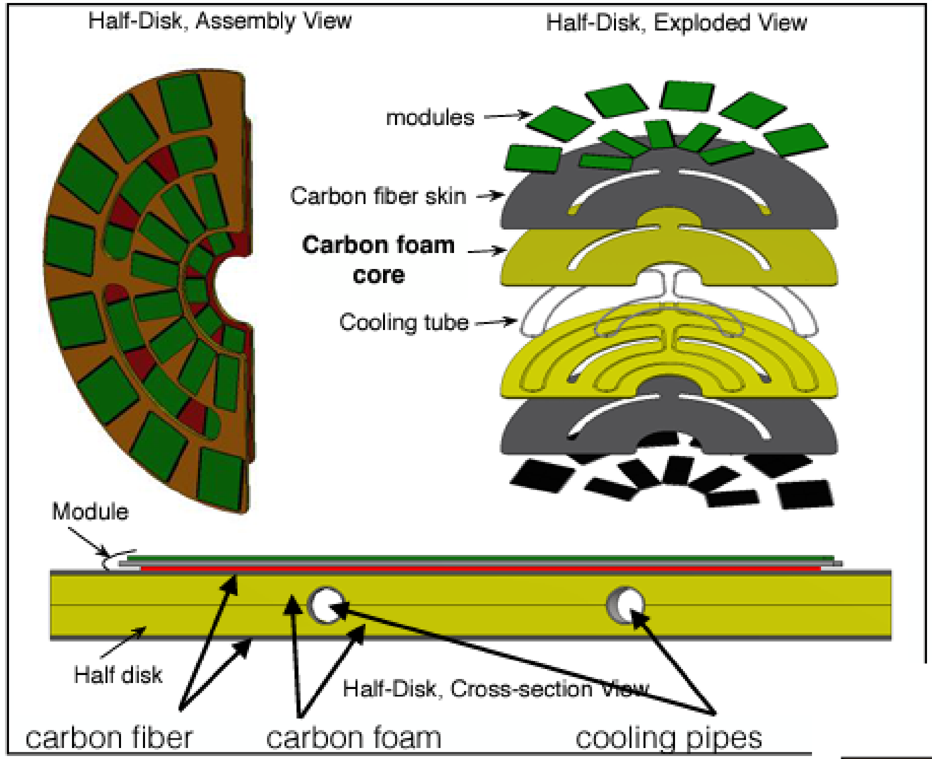




Terahertz Time Domain Spectroscopy – strain mapping

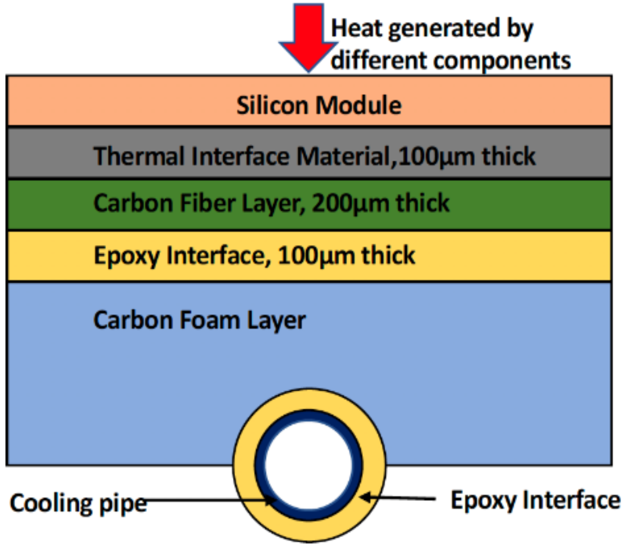
- Measurement of thermal and mechanical strains non-destructively in a composite Dee detector





Schematic of Dee cross section

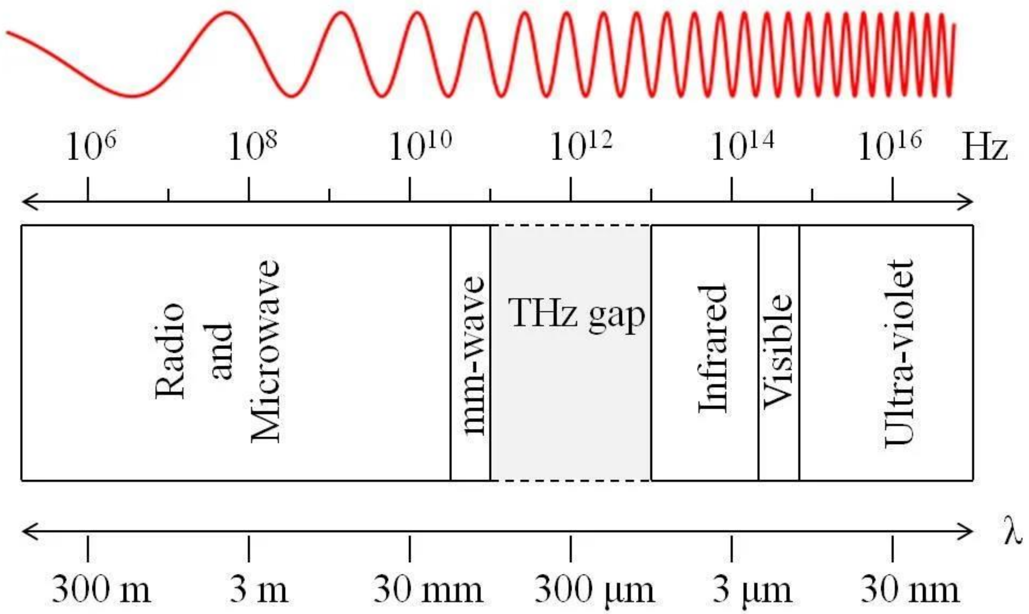
- Mechanical loads due to module weights
- Thermal loads due to CTE mismatch when Dee cooled to $-35°C$ using CO_2cooling

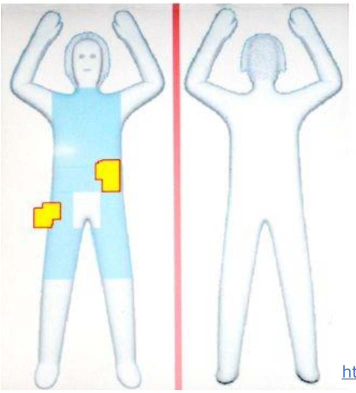


1. Introduction

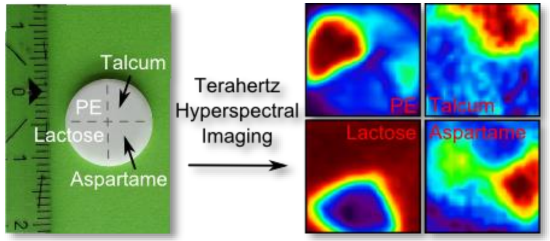
Ref: https://www.allaboutcircuits.com/technical-articles/introduction-to-terahertz/

- Tera Hertz Time Domain Spectroscopy allows
  - High transmission through visibly opaque materials
  - High resolution while avoiding scattering
  - High dynamic range, magnitude and phase recording with broad bandwidth
  - Quantifying small changes in dielectric properties of media
- Applications in security, chemistry, electronics, and now mechanics!



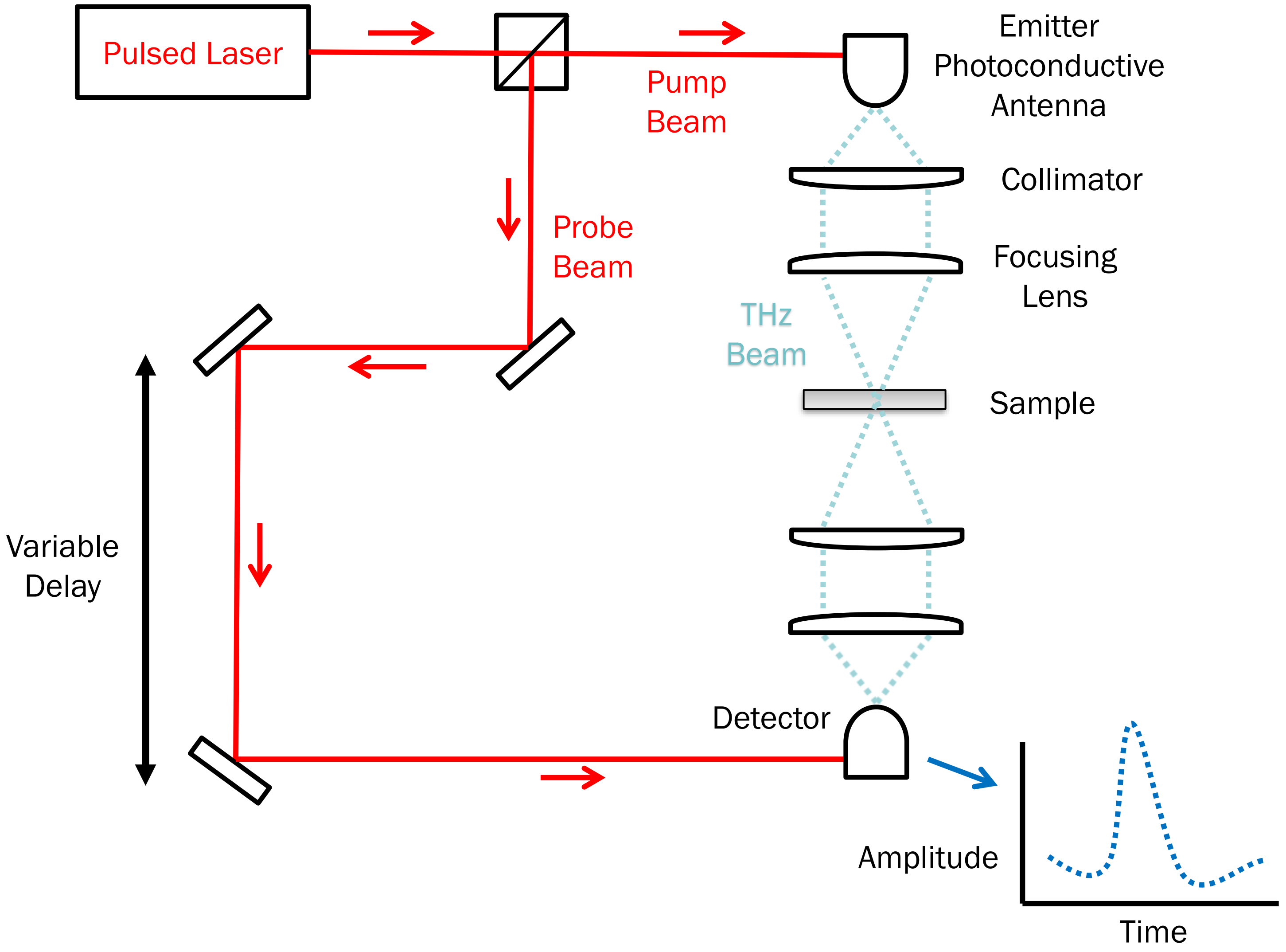


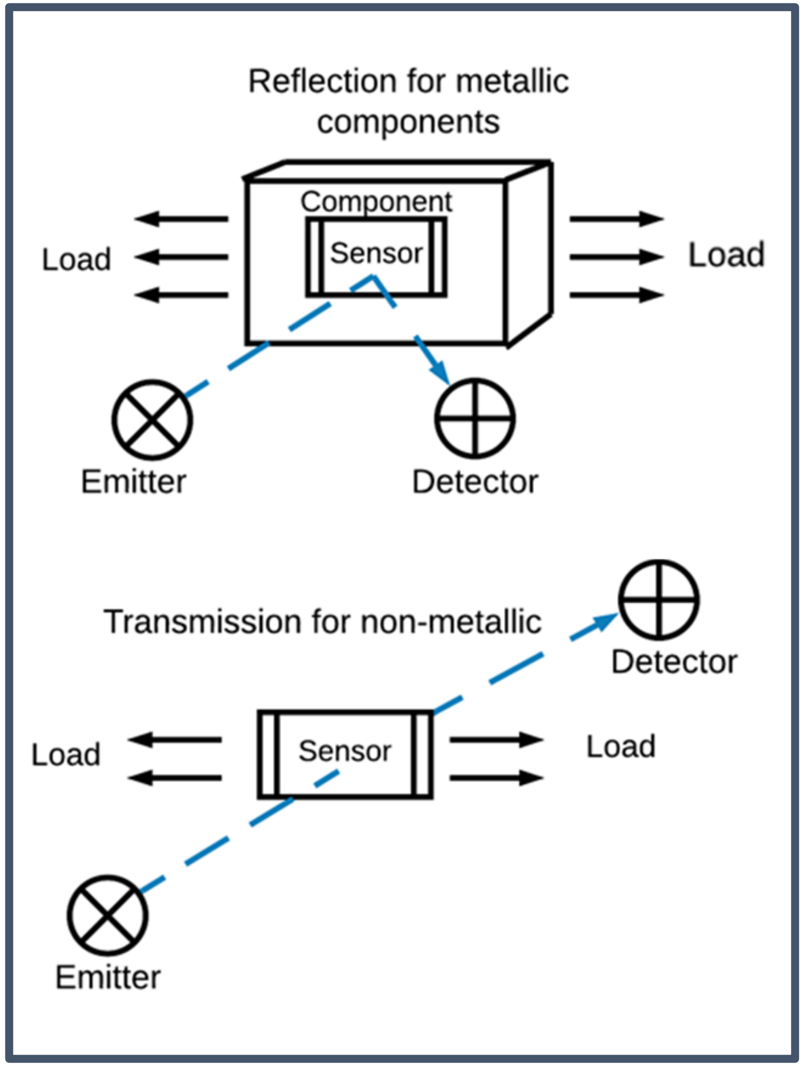
https://physics.aps.org/articles/v13/15



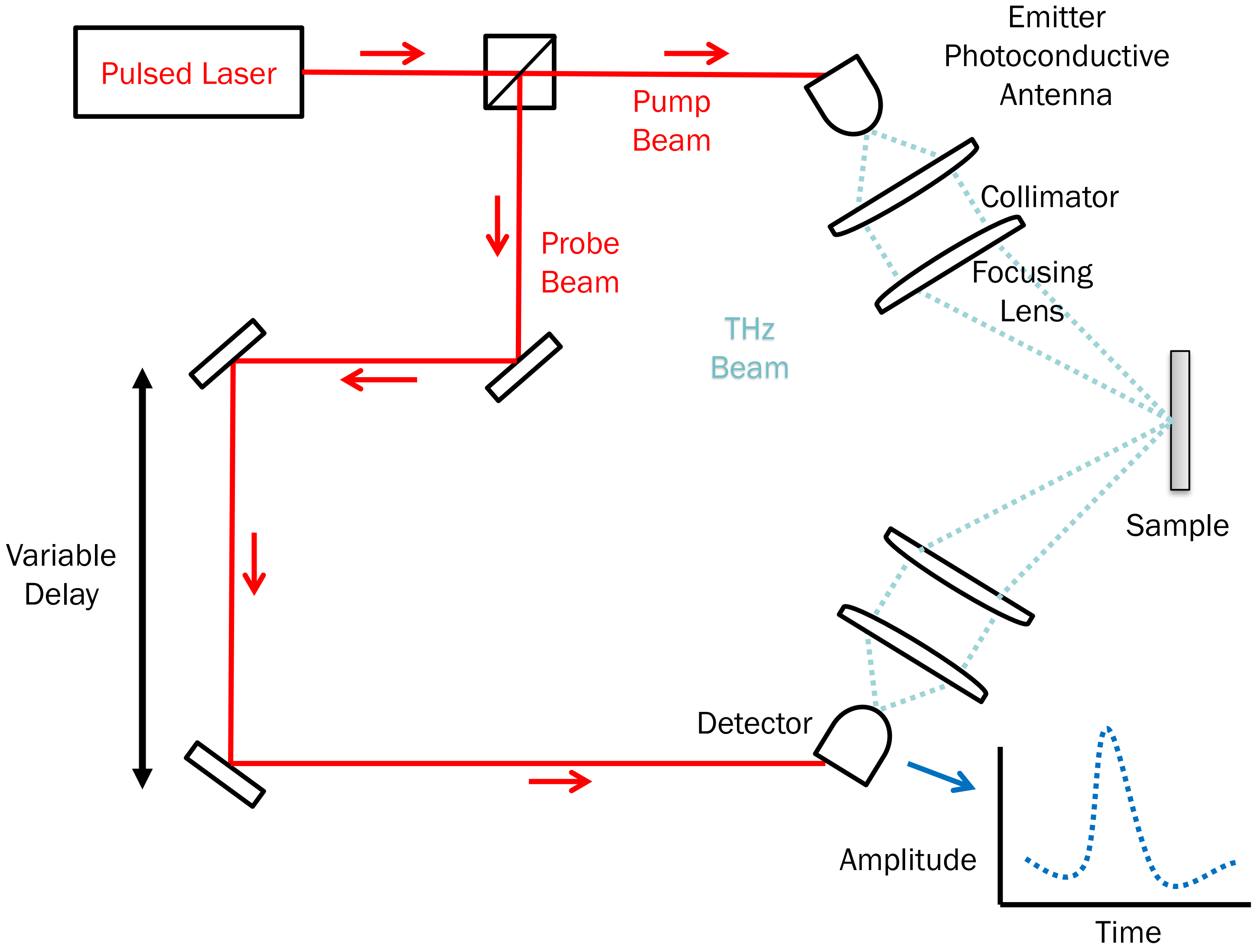
https://www.recendt.at/en/THz.html

Schematics for THz Spectroscopy set up





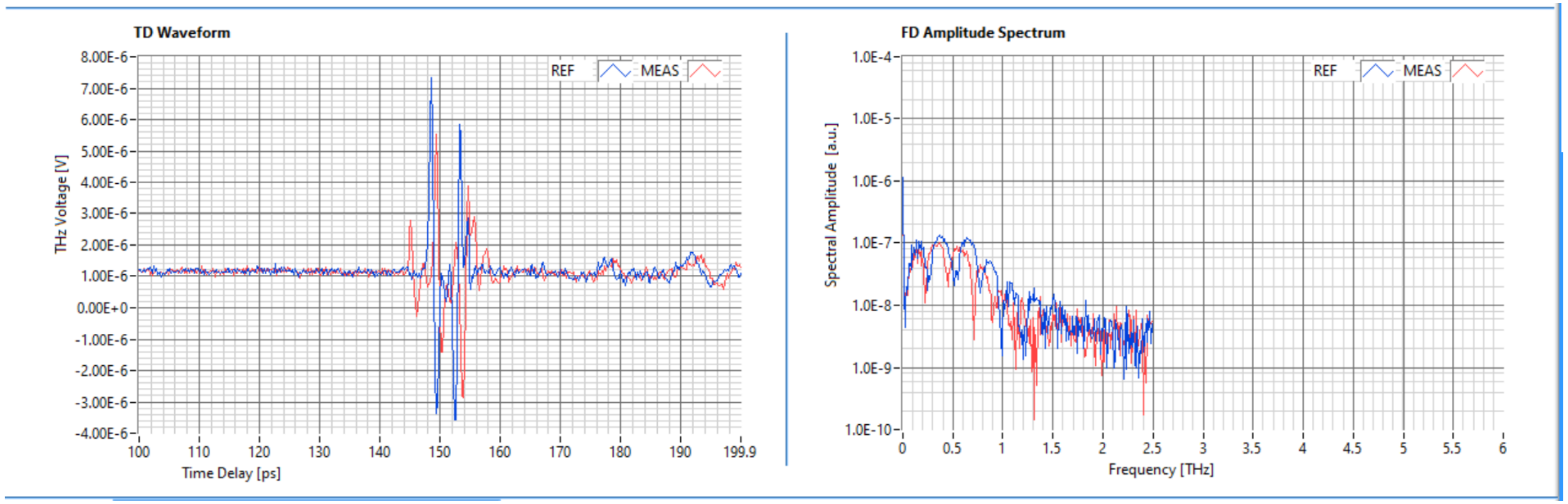
1. Introduction – Schematics for THz Spectroscopy set up

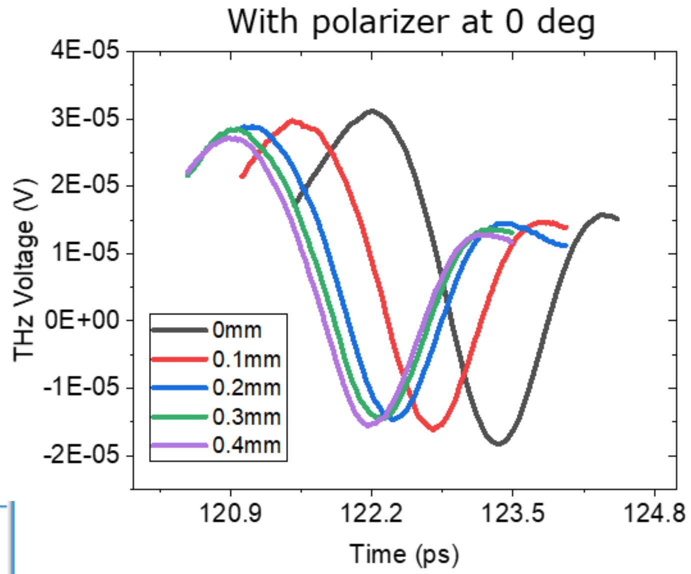


- A THz TDS set-up samples the amplitude of the wave as it reaches the detector antenna
- It works by splitting a pulsed laser for THz radiation generation into pump and probe beams and making a time domain measurements for the reflected/transmitted beam.
- Our set-up produces a resolution of 0.4mm through focusing lenses – measured using the knife edge method

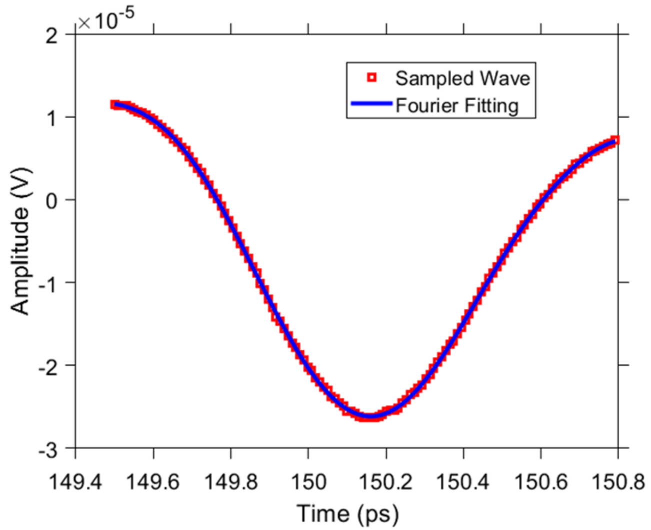
1. Introduction

THz temporal wave form data measured at each loading step → Curve smoothing and Fourier curve fitting to obtain peak positions → Computing ΔToA and correlation to strain response





THz wave form shift for deformation in a tensile test for dog bone specimen

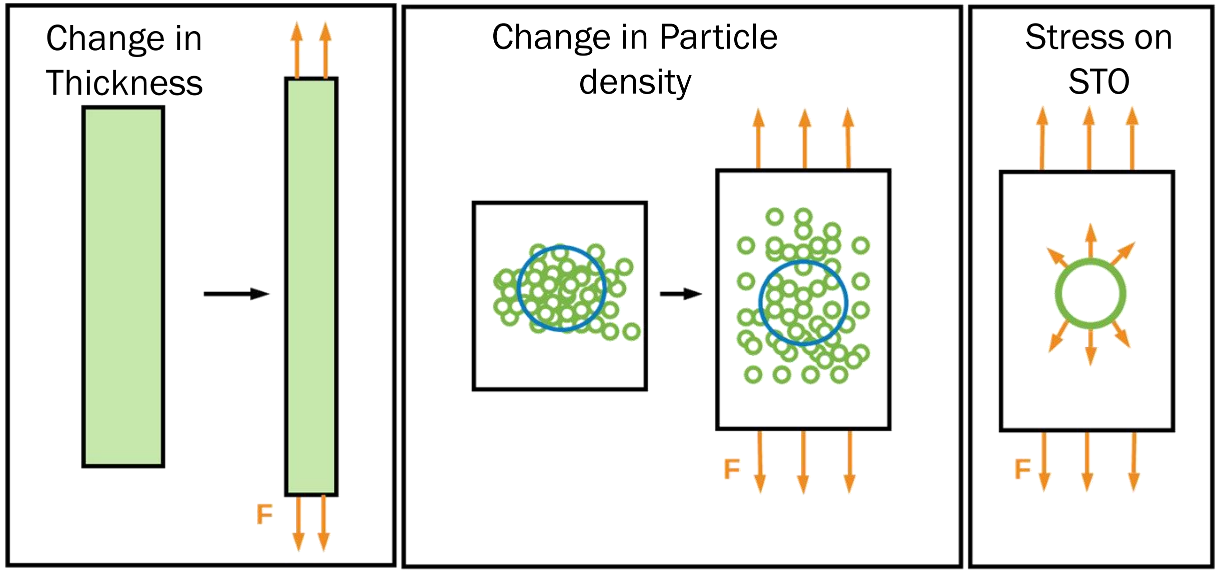


Literature Review: Other Remote Strain Sensing Methods

Strain Mapping Method	Comparison with THz TDS
Strain Gauges: • Optical Fiber Strain Sensors • Radio Wave Strain Sensors	-Sensors are highly reliable and widely available -Low spatial resolution
Optical Whole-Field Techniques: • Holography • Laser Speckle • DIC • Moiré • CT Scanning	-THz TDS will have lower resolution -THz TDS is not able to measure a whole-field at once -THz TDS could measure through opaque media
X-Ray Diffraction	-X-ray has high transmittivity and resolution -X-ray measures axial strain in a crystal -X-ray produces ionizing radiation
Raman Spectroscopy	-Raman has high resolution -Measures stresses -Does not penetrate opaque media

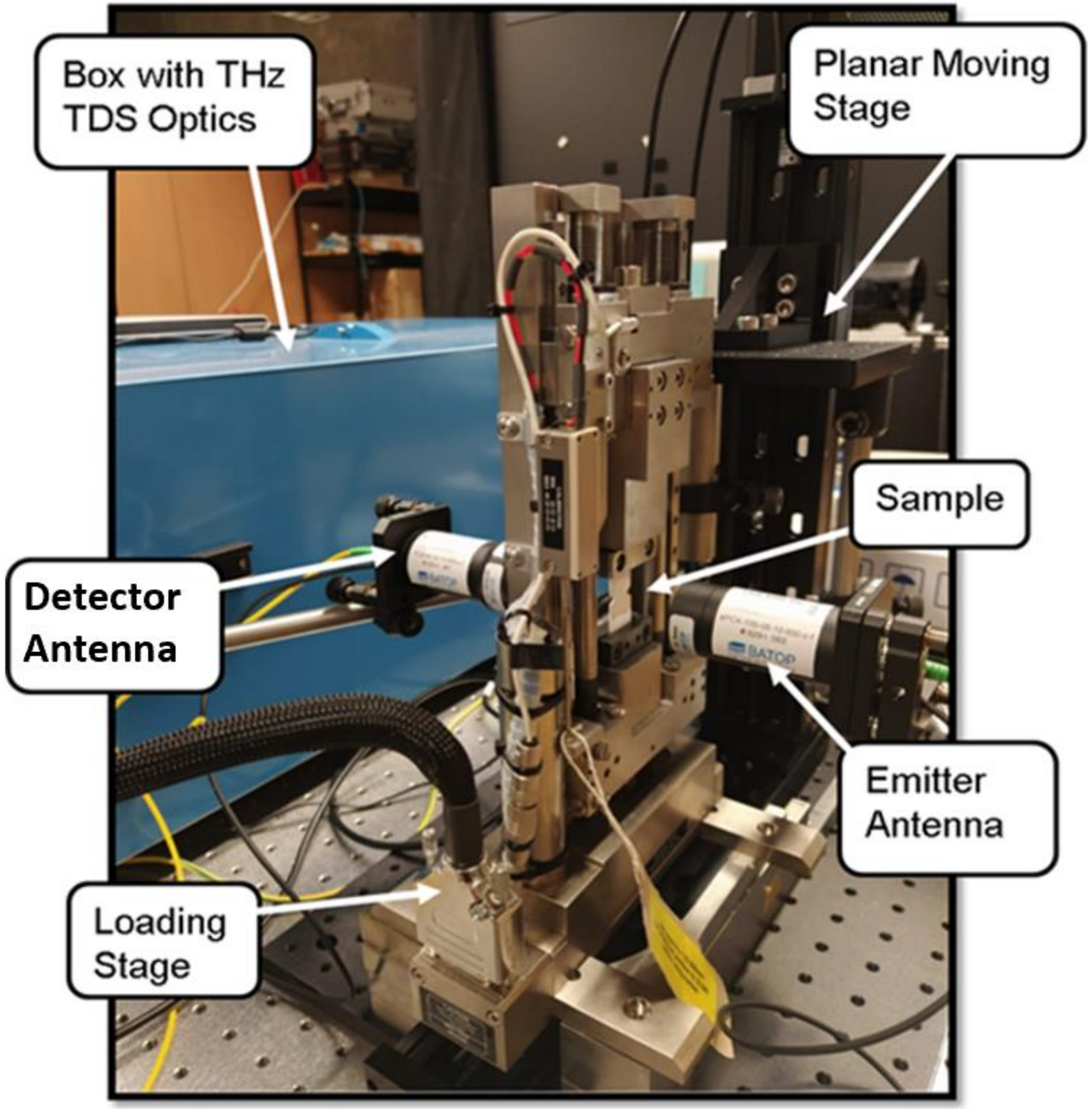
Presentation flow

THz Strain Measurement through STO Dielectrostrictive Composite



- Our sensor consists of high dielectric **strontium titanate (STO)** particles dispersed in an elastomer matrix (8% by wt)
- Strain will produce changes in the THz TDS response by:
  1. Change in thickness by Poisson's effect
  2. Dielectrostriction by change in high dielectric particles density.
  3. ~~Dielectrostriction by stress on STO~~

Measuring the THz wave response in time domain at different strain levels - Transmission set up

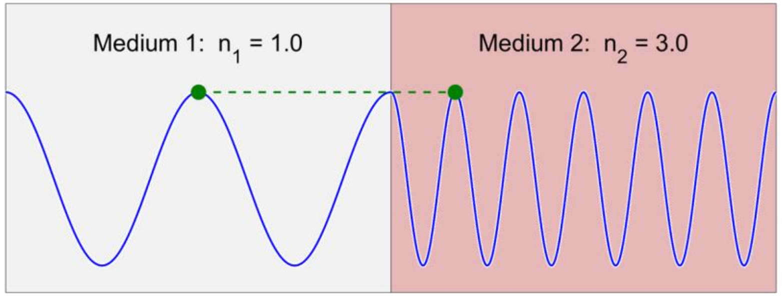


Mathematical modelling and data reduction

Velocity of wave in a media

$$v_w = \frac{c}{n} = \frac{c}{\sqrt{\varepsilon_r \, \mu_r}} \simeq \frac{c}{\sqrt{\varepsilon_r}}$$

Time of arrival $$ToA = \frac{d_{anten} - t_{sensor}}{v_{w,air}} + \frac{t_{sensor}}{v_{w,sensor}}$$



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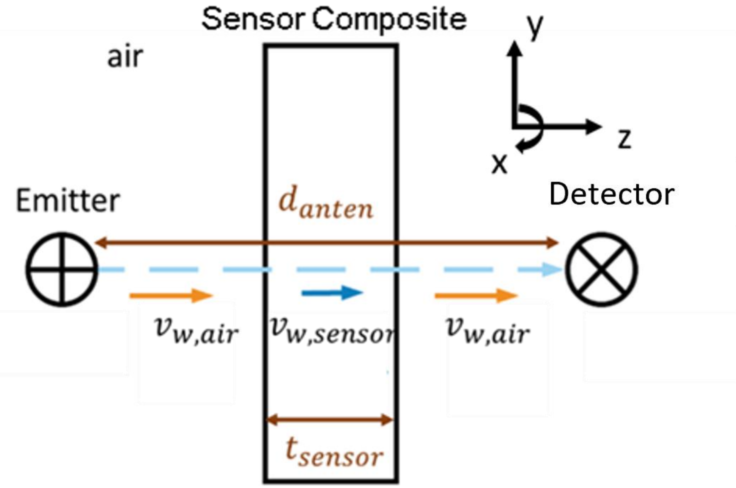
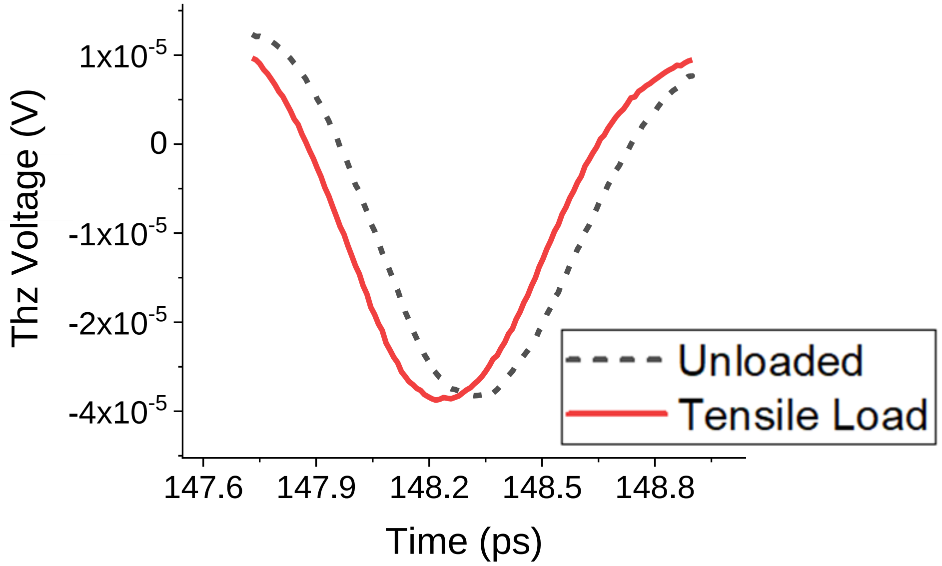




So, we measure $ToA_{xx}^{deformed}$ and $ToA_{xx}^{undeformed}$

Note that all the dielectric permitivities $, a_1, a_2$ (since $a_1, a_2 \rightarrow f(\varepsilon^0, \varepsilon^m)$) are directionally d pendent. Using corr lation equations, we compute the $\Delta ToA = ToA_{xx}^{deformed} - ToA_{xx}^{undeformed}$ simplified follows

$$\Delta ToA_{xx} \cdot \left(\frac{c}{t_0}\right) = \left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right) \cdot \left(\left(\varepsilon^0 + a_1 \cdot \frac{-\nu \cdot e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})\right)^{\frac{1}{2}} - 1\right) + \sqrt{\varepsilon^0} - 1$$

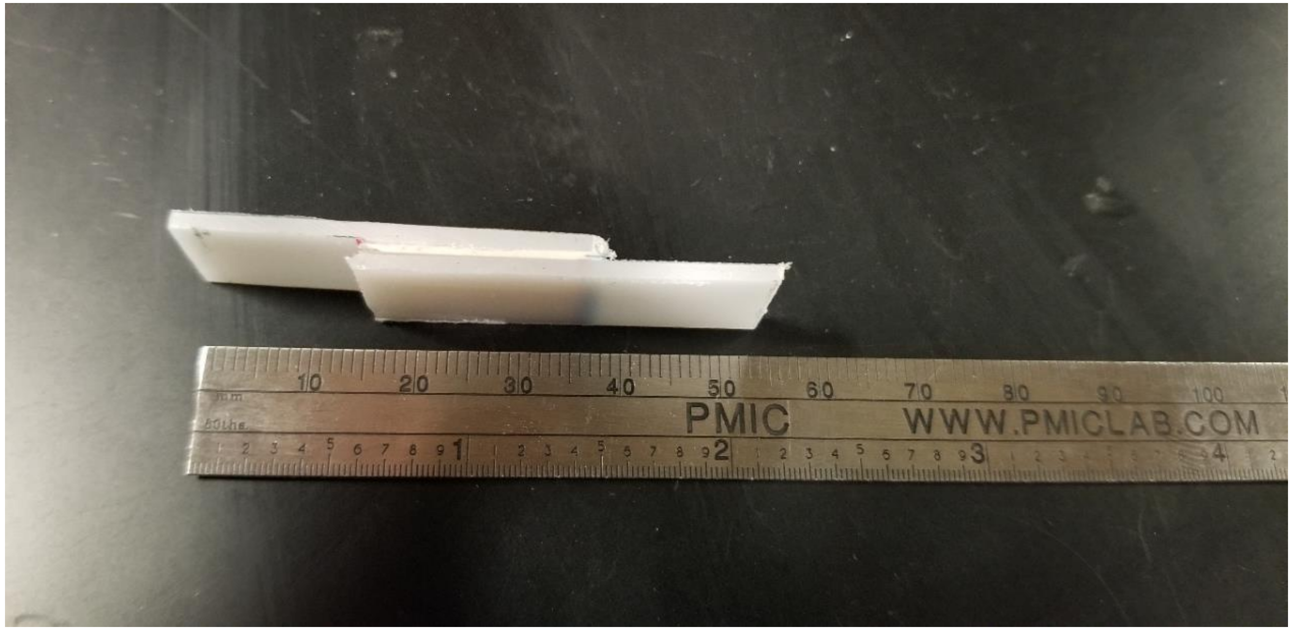
$$\Delta ToA_{yy} \cdot \left(\frac{c}{t_0}\right) = \left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right) \cdot \left(\left(\varepsilon^0 + a_1 \cdot \frac{e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})\right)^{\frac{1}{2}} - 1\right) + \sqrt{\varepsilon^0} - 1$$

Presentation flow

Measurement of volumetric strain for a simple open hole tensile and lap shear specimens

Circular Hole Tensile Testing

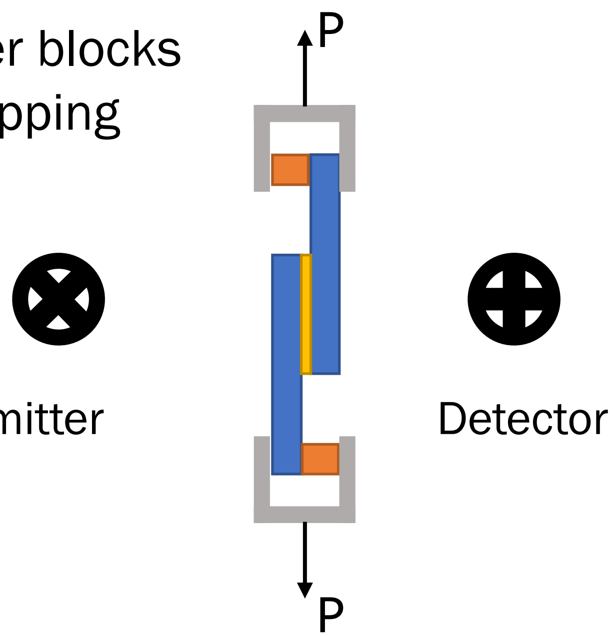
Lap Shear specimen



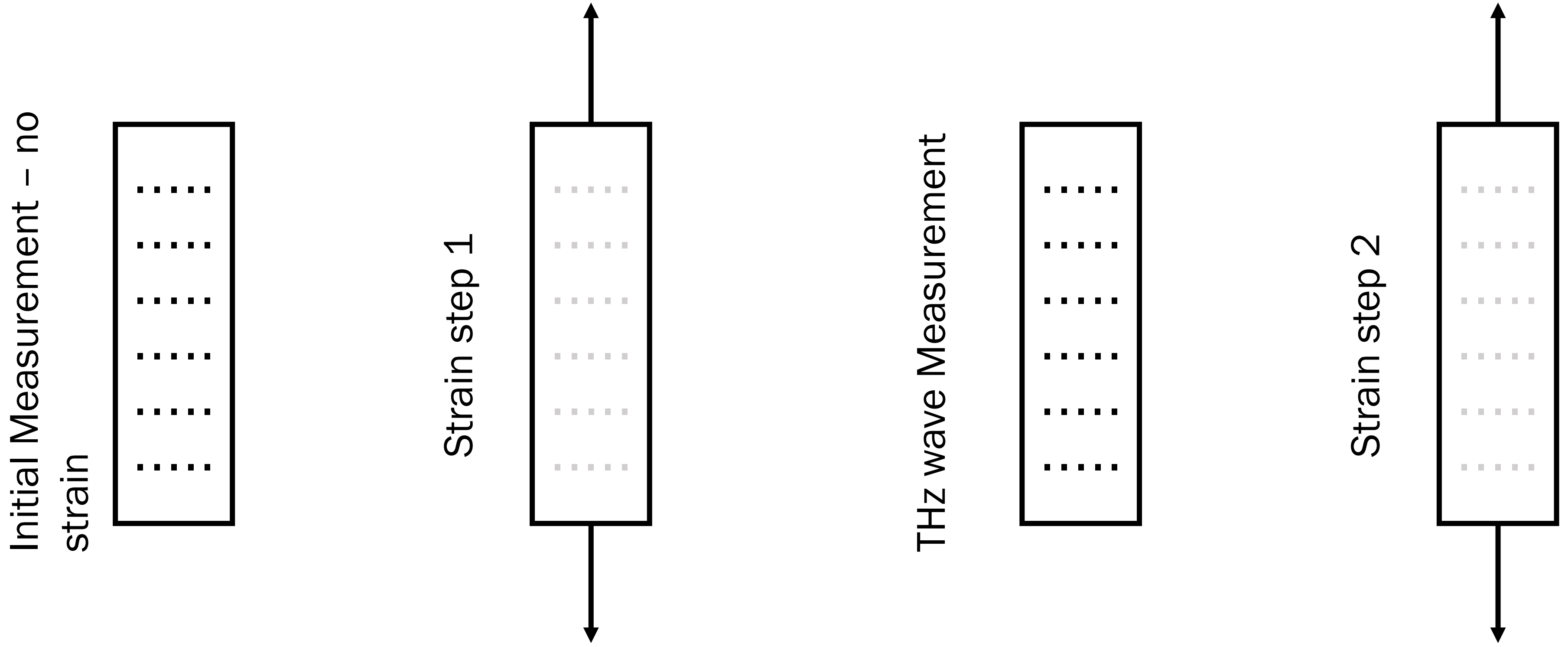
Experimental set up – STO (8% wt) + PDMS composite ‘adhesive’ on a HDPE base plate –transmission mode

- HDPE strips
- STO + PDMS
- Spacer blocks for gripping

Single Lap Shear Testing

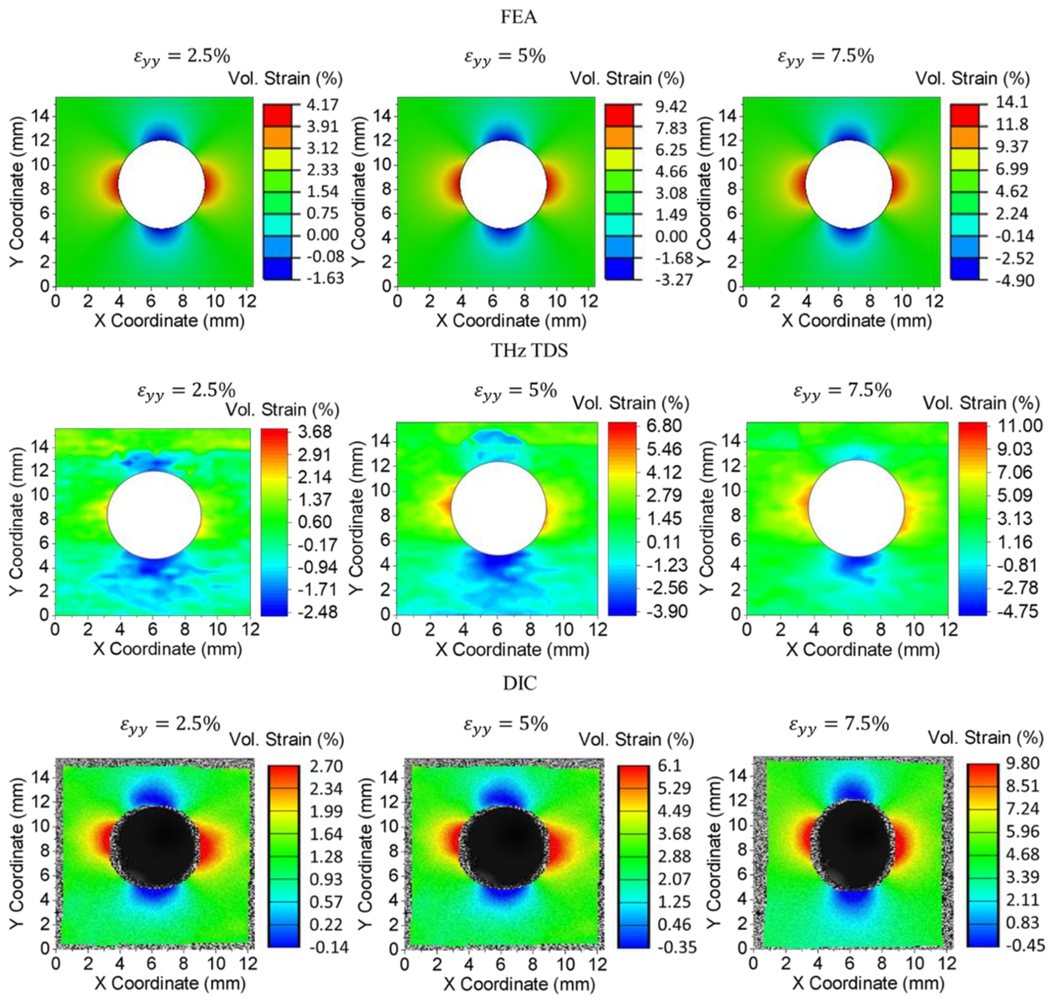


Measurement methodology



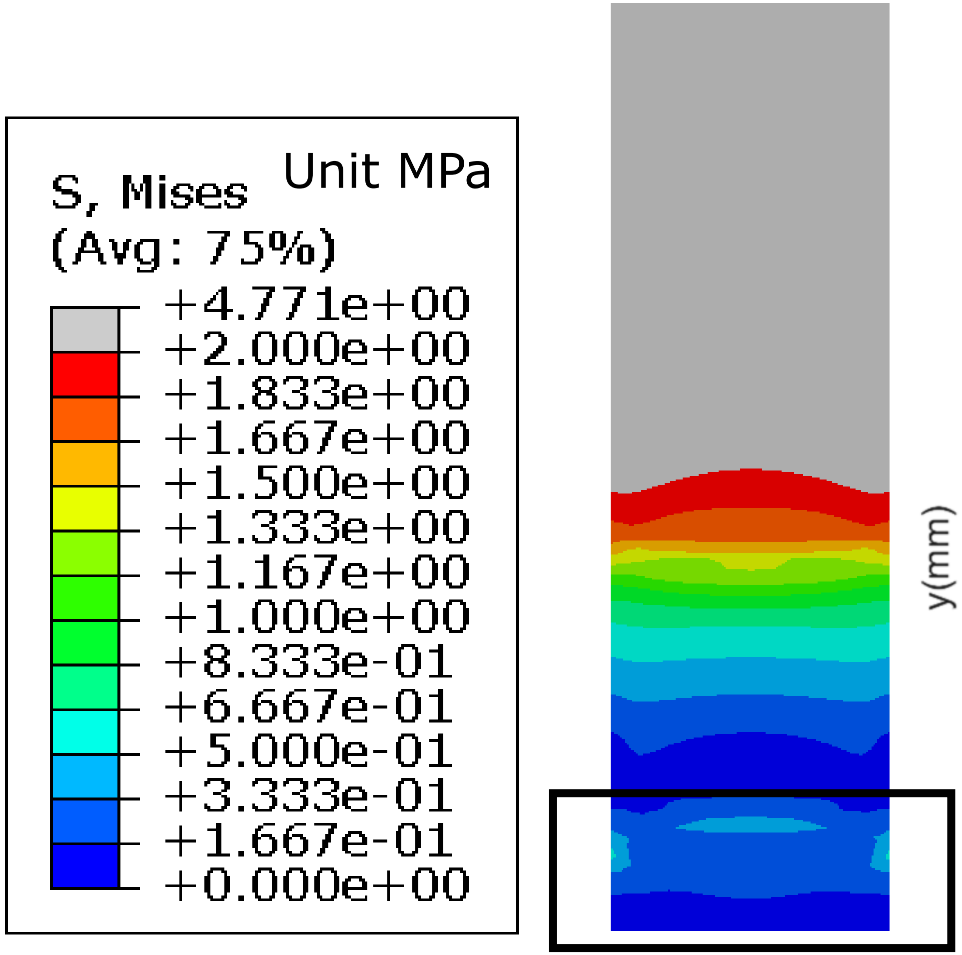
…… and repeat

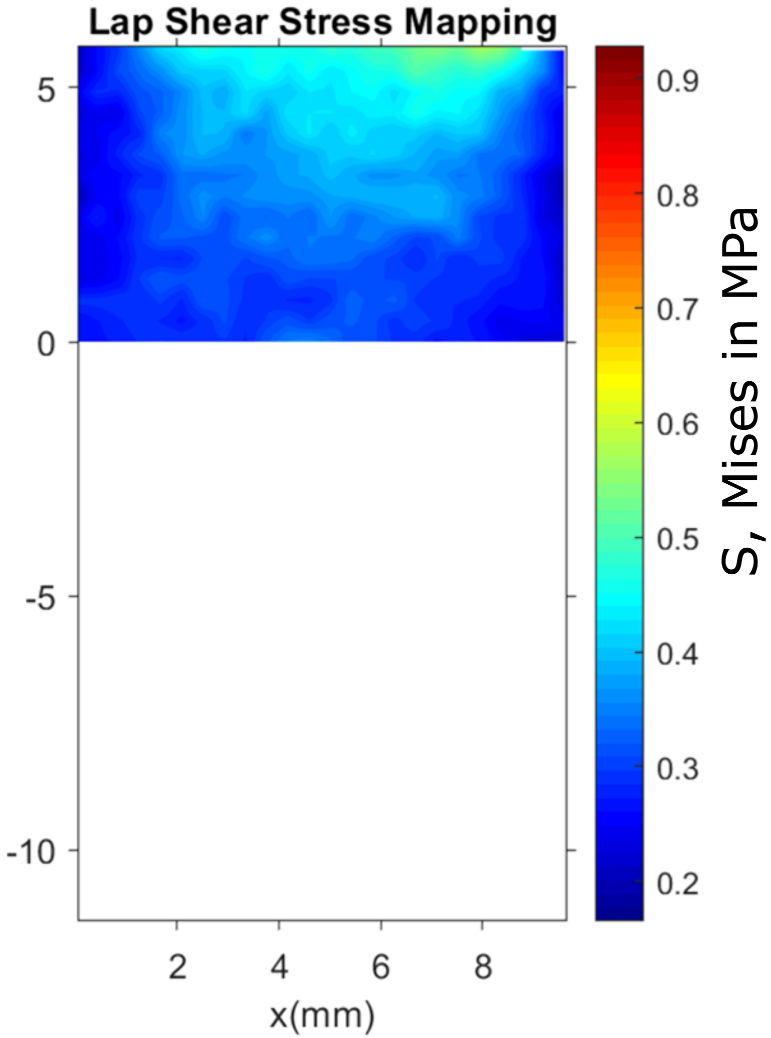
Open hole tensile test

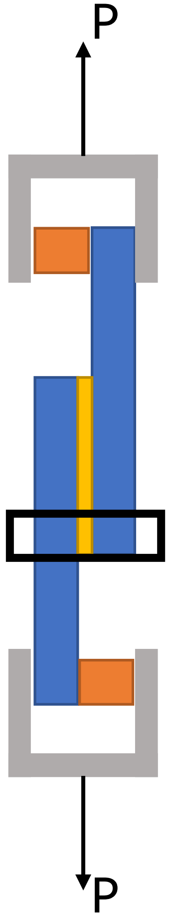


- Test results for a TRANSMISSION mode measurement with sample made from STO + PDMS
- We can capture good results for tensile load cases. Good correlation seen between the THz-TDS measurements, FEA and DIC measurements

Lap Shear Test – FEA analysis – Cohesive surface model – comparison to THz- TDS scan







PRELIMINARY RESULTS

Conclusions and summary

1. Tera-hertz time domain spectroscopy shows promise for interface strain and stress measurements by using passive sensor media, a baseline approach for the same has been established in this study.

2. The corelation of time or arrival and the strain/stress state in a loaded state (either thermal or mechanical or combined loading) is the novelty of this research.

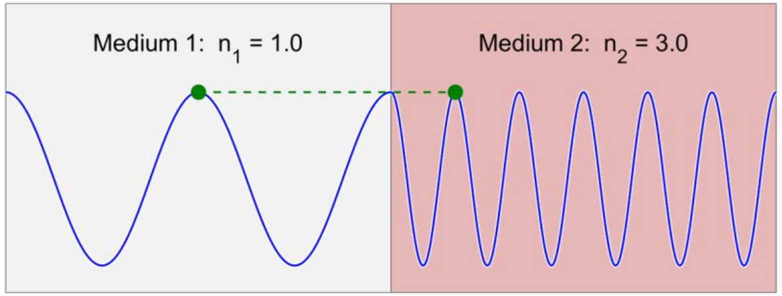
3. Future research will enable in-situ measurement of interface strain in bi-material and multi-material interfaces.

Thank you

Questions ?

Back up slides

Mathematical modelling and data reduction



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v_w – velocity of wave

n – refractive index

ε_r – dielectric permittivity

$e_{vol}, e_{xx}, e_{yy}, e_{zz}$ – strains in local coordinate system

t_f, t_o – final thickness and initial thickness of sample

$\varepsilon^0 = \varepsilon^i$ – dielectric permittivity of undeformed composite (here PDMS + 8% STO)

ε_{eff} – effective dielectric permittivity of deformed composite as a function of strain

c – speed of light

μ_r – magnetic permeability

ToA – time of arrival of a wave

e_{11}, e_{22}, e_{33} – principal strains

ν – Poisson's ratio

ε^m – dielectric permittivity of matrix material (here PDMS)

d_{anten} – distance between the antennae

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ν – Poisson's ratio
ε^m – dielectric permittivity of matrix material (here PDMS)
d_{anten} – distance between the antennae

The velocity of a wave in a media is given by

$$v_w = \frac{c}{n} = \frac{c}{\sqrt{\varepsilon_r\, \mu_r}} \simeq \frac{c}{\sqrt{\varepsilon_r}} \qquad \text{(i.)}$$

The volumetric strain in a thin plate can be approximated to

$$e_{vol} = e_{xx} + e_{yy} + e_{zz} \qquad \text{(ii.)}$$

$$e_{xx} = \frac{-\nu \cdot e_{vol}}{1 - 2\nu}$$

$$e_{yy} = \frac{e_{vol}}{1 - 2\nu}$$

$$e_{zz} = \frac{-\nu \cdot e_{vol}}{1 - 2\nu}$$

On tensile loading of the sample there is a thickness change in the sample that is given by

$$t_f = t_0\left(1 - \frac{\nu \cdot e_{vol}}{1 - 2\nu}\right) \qquad \text{(iii.)}$$

The effective dielectric permittivity will be dependent on the volumetric strain at each step and is given by Shkel Y.M. and Klingenberg D.J. (1998) as follows

$$\varepsilon_{ij} = \varepsilon^0 \cdot \delta_{ij} + a_1 \cdot e_{ij} + a_2 \cdot e_{kk} \cdot \delta_{ij} \rightarrow \begin{cases} \varepsilon_{11} = \varepsilon^0 + a_1 \cdot e_{11} + a_2 \cdot (e_{vol}) \\ \varepsilon_{22} = \varepsilon^0 + a_1 \cdot e_{22} + a_2 \cdot (e_{vol}) \\ \varepsilon_{33} = \varepsilon^0 + a_1 \cdot e_{33} + a_2 \cdot (e_{vol}) \end{cases} \quad \text{(iv.)}$$

$$a_1 = -\frac{2}{5}\frac{(\varepsilon^0 - \varepsilon^m)^2}{\varepsilon^m}$$

$$a_2 = -\frac{1}{3}\frac{(\varepsilon^i - \varepsilon^m)(\varepsilon^i + 2\varepsilon^m)}{\varepsilon^m} + \frac{2}{15}\frac{(\varepsilon^i - \varepsilon^m)^2}{\varepsilon^m}$$

The time of arrival of a wave is given by

$$ToA = \frac{d_{anten} - t_{sensor}}{v_{w,air}} + \frac{t_{sensor}}{v_{w,sensor}} \quad \text{(v.)}$$

Hence for undeformed sample with no strain, which is the initial case we have

$$ToA^{undeformed} = \frac{d_{anten}}{\mathrm{c}} - \frac{t_o}{c} + \frac{t_o}{\mathrm{c}}\sqrt{\varepsilon^0} \quad \text{(vi.)}$$

for the deformed sample we use the final thickness given by equation iii.

(vii.)

$$ToA_{xx}^{deformed} = \frac{d_{anten}}{\mathrm{c}} - \frac{t_f}{c} + \frac{t_f}{\mathrm{c}}\sqrt{\varepsilon_{11}}$$

$$ToA_{xx}^{deformed} = \frac{d_{anten}}{\mathrm{c}} - \frac{t_0\left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right)}{c} + \frac{t_0\left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right)}{\mathrm{c}}\sqrt{\varepsilon^0 + a_1 \cdot \frac{-\nu \cdot e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})}$$

Note that all the dielectric permittivities ε^0, a_1, a_2 (since $a_1, a_2 \rightarrow f(\varepsilon^0, \varepsilon^m)$) are directionally dependent. Using these equations, we compute the $\Delta ToA = ToA_{xx}^{deformed} - ToA_{xx}^{undeformed}$ simplified follows

(viii.)

$$\Delta ToA_{xx} \cdot \left(\frac{c}{t_0}\right) = \left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right) \cdot \left(\left(\varepsilon^0 + a_1 \cdot \frac{-\nu \cdot e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})\right)^{\frac{1}{2}} - 1\right) + \sqrt{\varepsilon^0} - 1$$

$$\Delta ToA_{yy} \cdot \left(\frac{c}{t_0}\right) = \left(1 - \frac{\nu \cdot e_{vol}}{1-2\nu}\right) \cdot \left(\left(\varepsilon^0 + a_1 \cdot \frac{e_{vol}}{1-2\nu} + a_2 \cdot (e_{vol})\right)^{\frac{1}{2}} - 1\right) + \sqrt{\varepsilon^0} - 1$$

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