Modelling and Fabrication of High Frequency Ultrasound Transducer Arrays for Medical Applications

Robert T. Ssekitoleko
DTC in Medical Devices, University of Strathclyde

Gerry Harvey
Weildlinger Associates, Ltd (PzFlex Europe)

Christine E.M. Démoré, Zhen Qiu, Muhammad. R. Sadiq, Sandy Cochran
Institute of Medical Science and Technology, University of Dundee

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Outline

Background

- Ultrasound Systems and Applications
- High Frequency Imaging
- Ultrasonic Device Development

Miniature Array Design

- Design Specification

Fabrication Techniques

- Bonding and Interconnects

Single Crystal Piezoelectric Materials

- Piezoelectric Material Characterisation

Virtual Prototyping

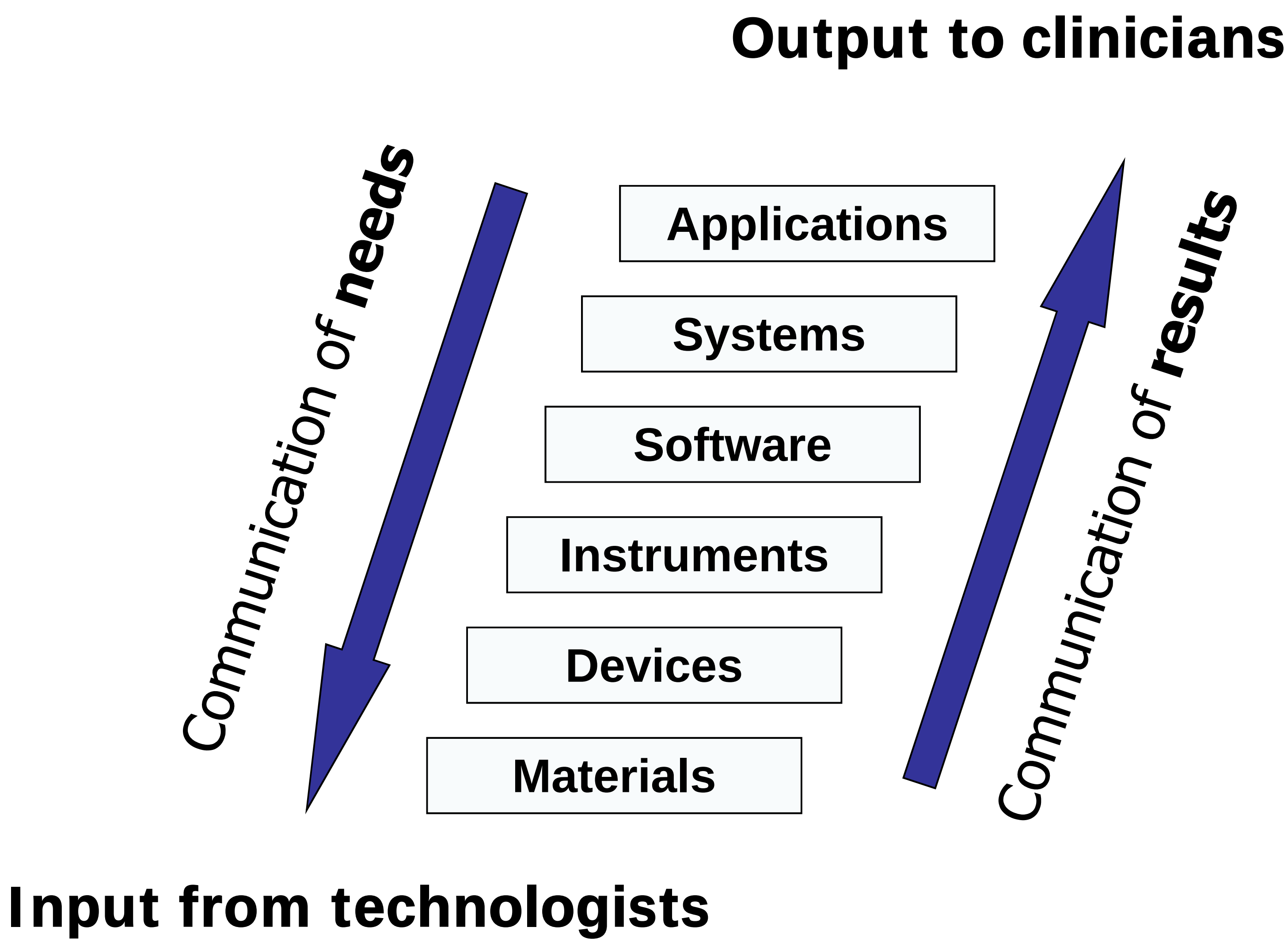
- Preliminary Results
- 15 MHz virtual prototyped transducer

Basic Fabricated Prototype

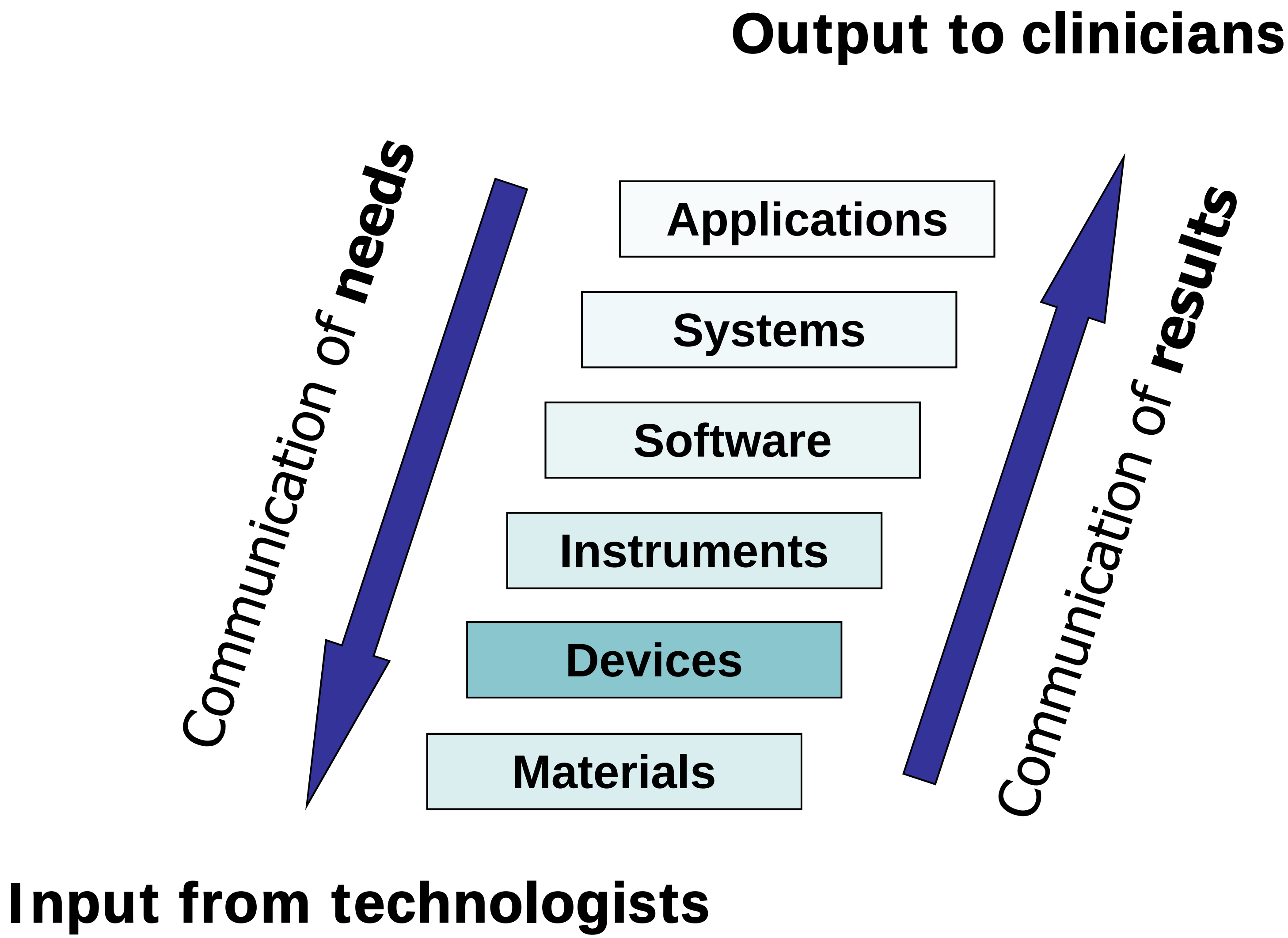
Summary & Conclusions

Further Work

Ultrasound Systems and Applications



Ultrasound Systems and Applications



High Frequency Imaging

Increasing operational frequency improves image resolution

- 15 MHz and above give image resolution of less than 0.5 mm

Main applications include:

Intravascular imaging

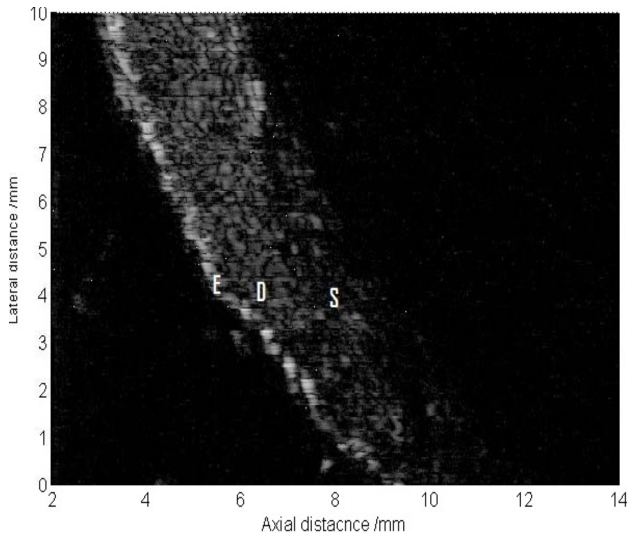
Small animal imaging

Ophthalmology

Dermatology

BUT

Increasing frequency reduces depth of penetration due to frequency dependent attenuation

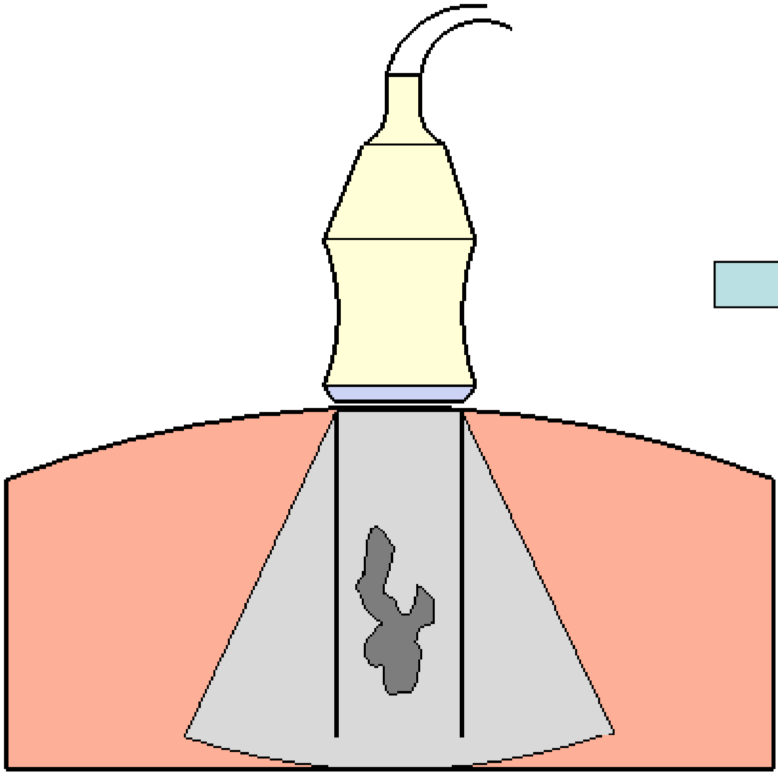


Skin layers imaged with 32 MHz transducer. The epidermis (E), Dermis (D) and subcutaneous (S) layers are clear

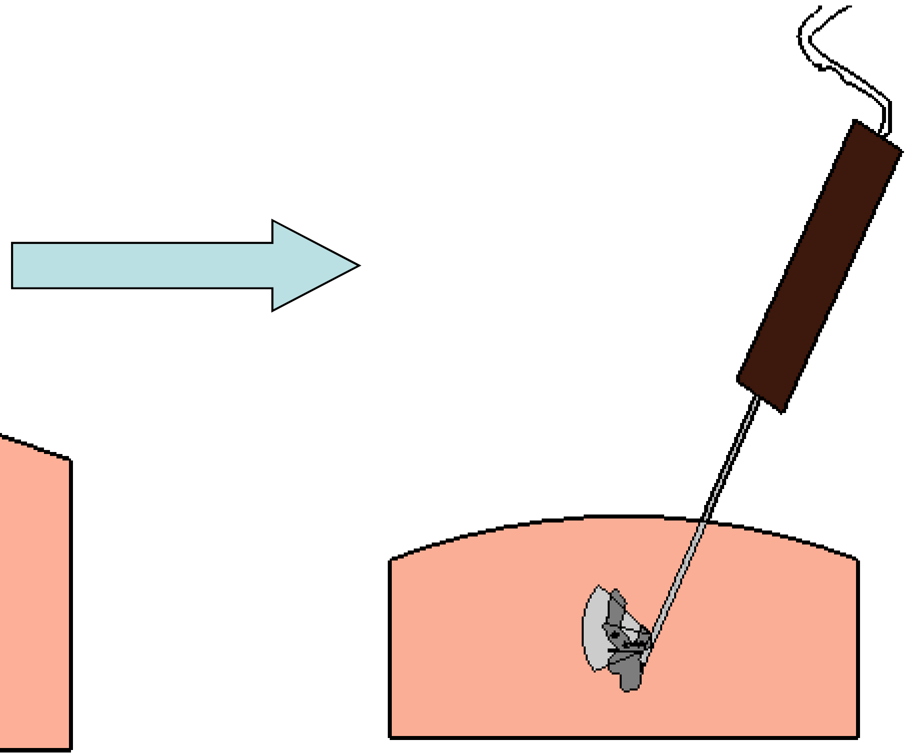
[1] R. T. Ssekitoleko et al:Progress In High Resolution Ultrasound Towards In Vivo Pathology: SMIT 2010

Transducer on Interventional Tool

Conventional
Ultrasound Probe



Miniature array on a
biopsy needle



Transducer on Interventional Tool

Transducer size reduces with increasing frequency

- 15 MHz array has dimensions small enough to fit in a tool with a diameter of 2 mm

Imaging transducers on interventional tools overcomes the attenuation problem

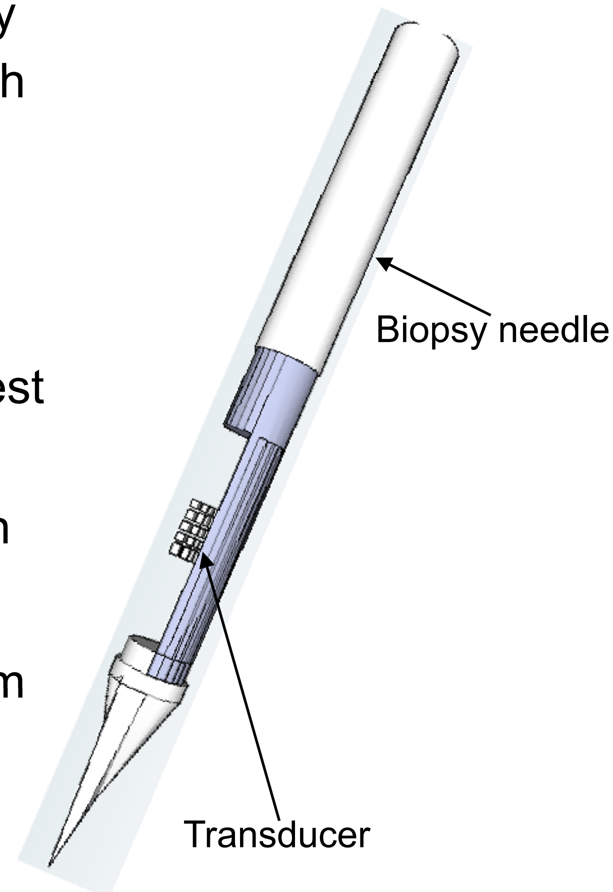
- Can be placed at the tissue region of interest

Accurate and quick characterisation of tissues with high resolution images

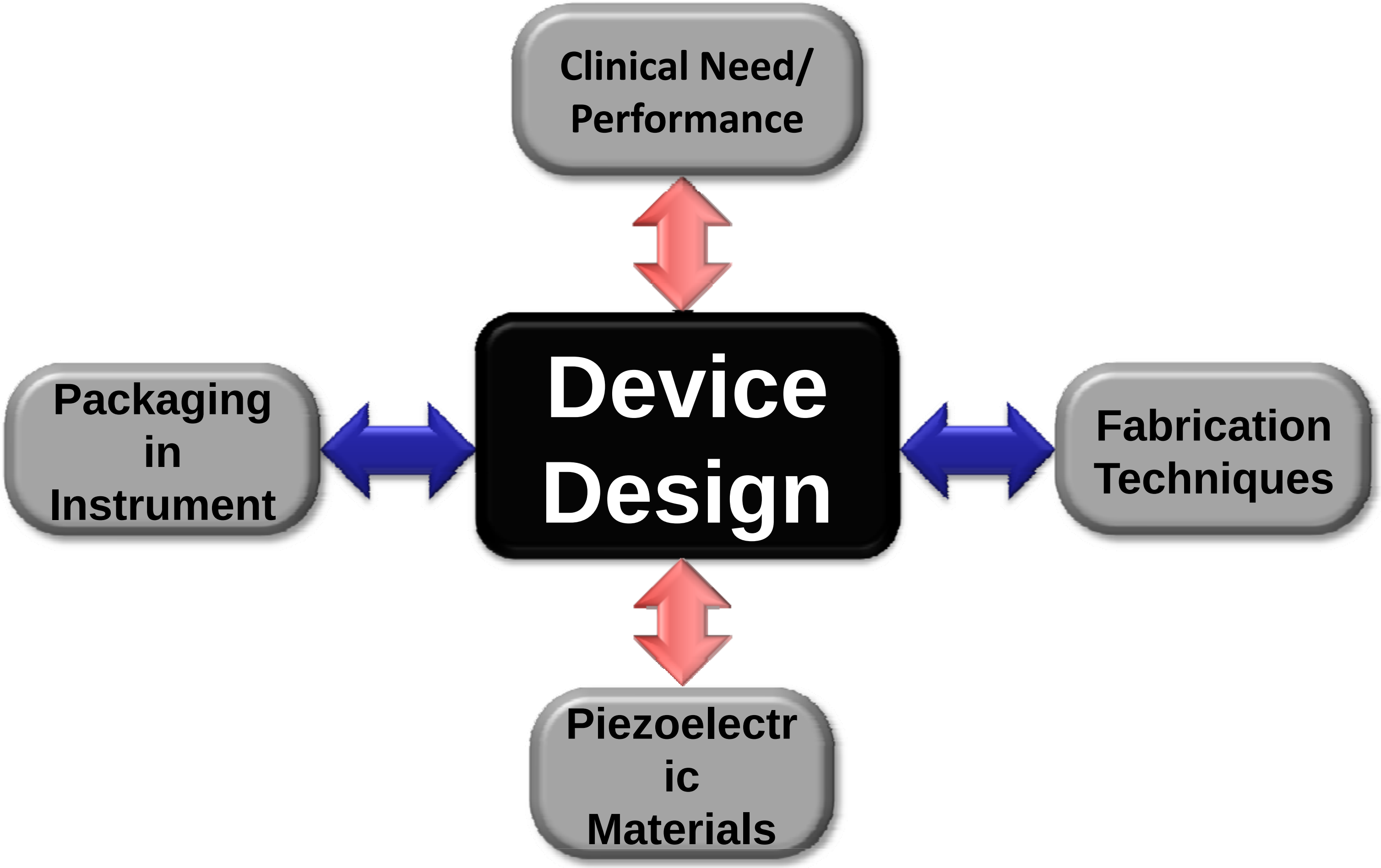
- Miniature arrays enable real-time imaging with electronic scanning of ultrasound beam

Potential for ultrasound *in vivo* pathology

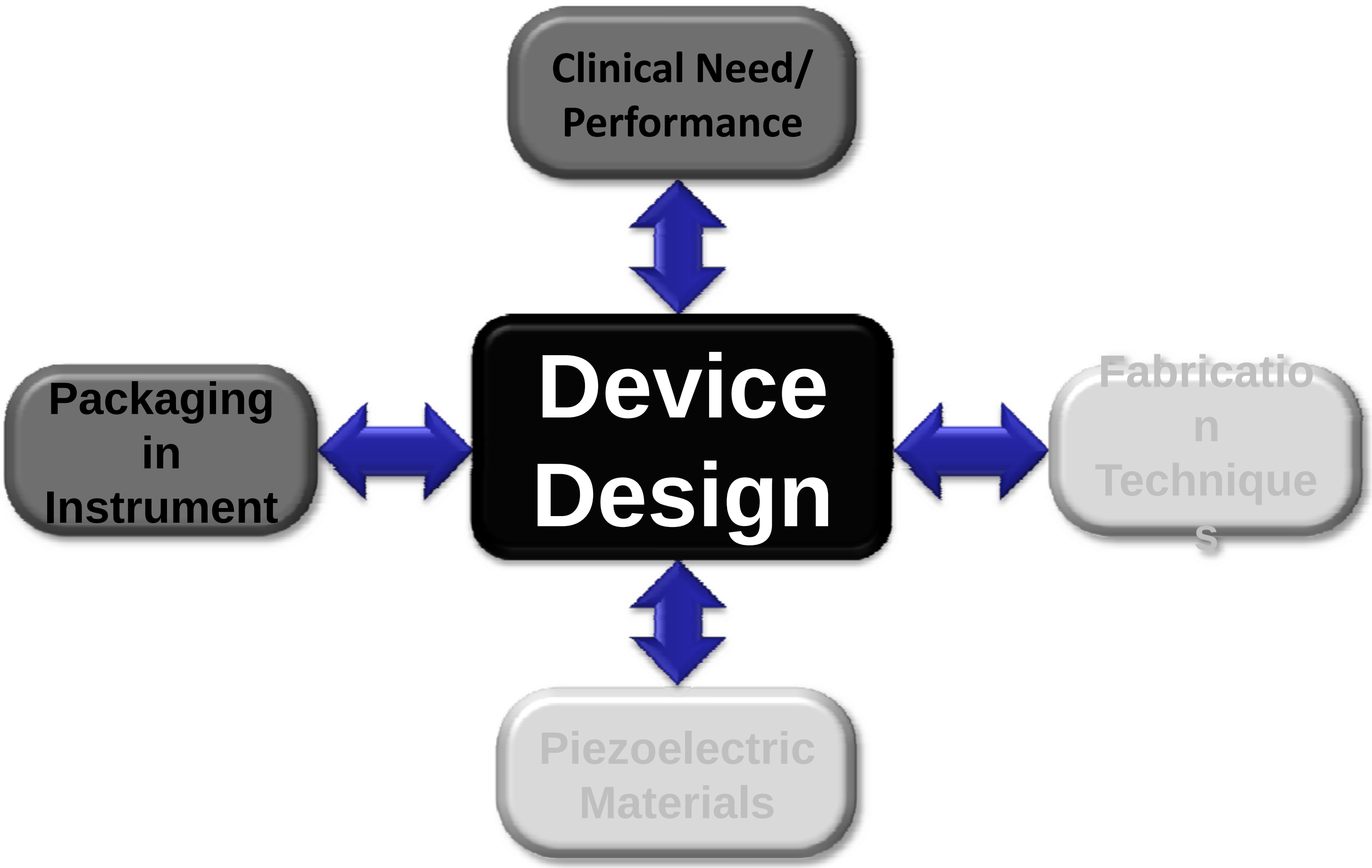
- Accurately positioned tissue biopsies for staging disease



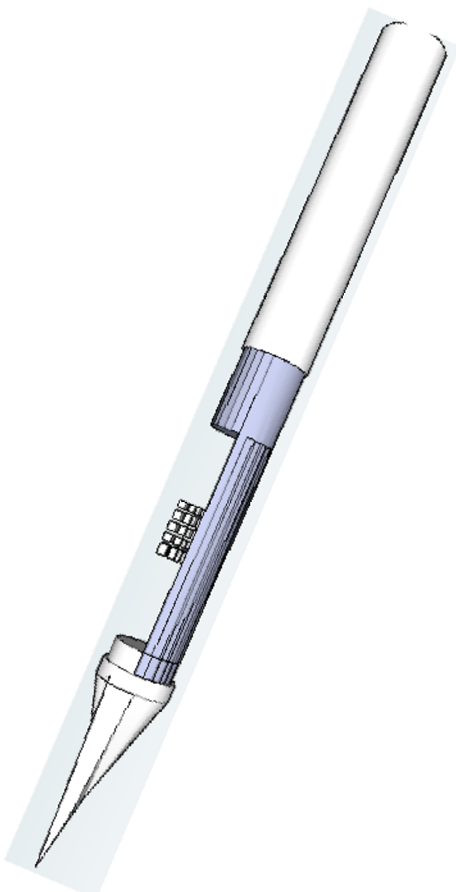
Ultrasonic Device Development



Miniature Array Design



Design Specification



Application:	Imaging of small, deep-seated tumours
Interventional tool:	2 mm diameter biopsy needle
Array Type:	Linear array for electronic scanning Side viewing for rectilinear image
Image resolution:	100 µm or better
Imaging frequency:	15 MHz or higher

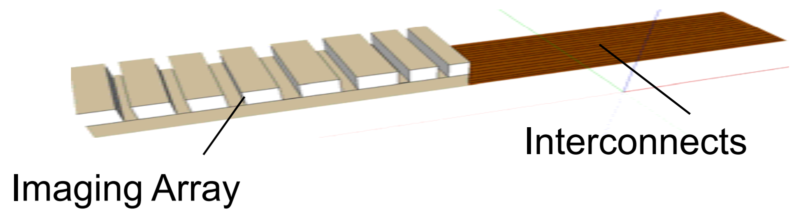
Design Specification

Initial Array Specification

Piezoelectric layer: 1-3 piezocomposite with single crystal PMN-PT and hard-setting epoxy

Matching layer: Alumina loaded epoxy

Backing layer: Tungsten loaded epoxy

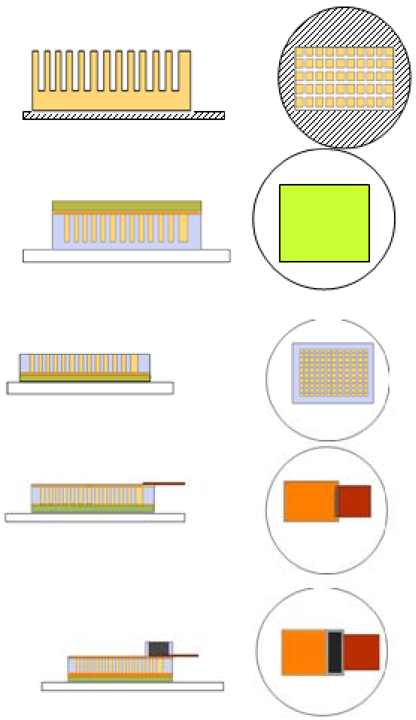


Array elements: 64 elements
100 µm pitch (λ at 15 MHz)

Array dimensions: 0.8 mm wide
6.4 mm long

Cabling: Flex circuit cabling to fit in core of 2 mm biopsy needle

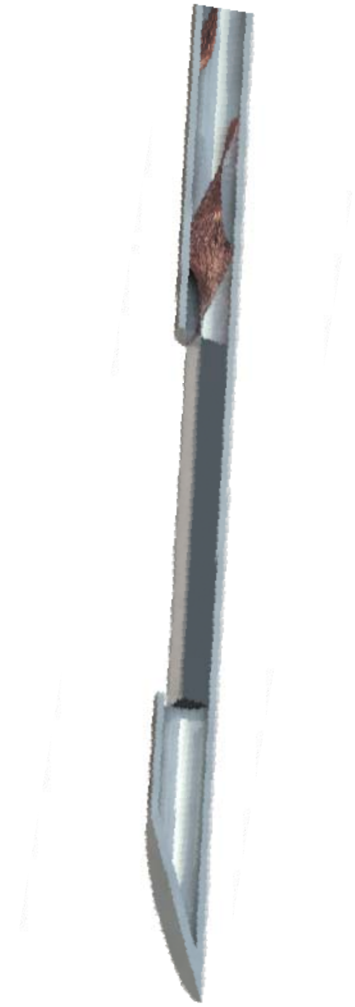
Basic Array Implementation



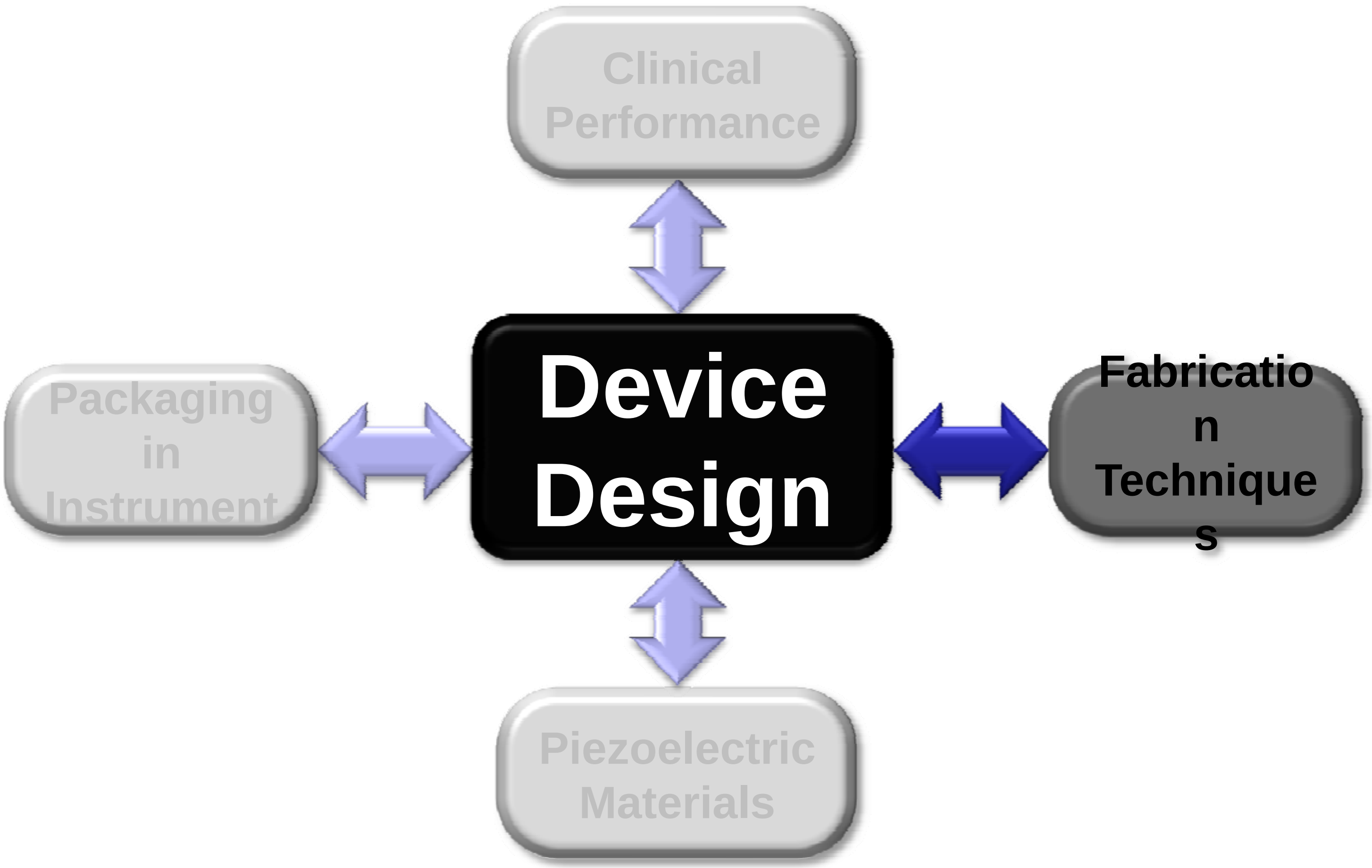
- Process diagram is fully defined

- Technical challenges have been outlined and solutions investigated

- Packing technique for the needle orientation is established



Fabrication Techniques



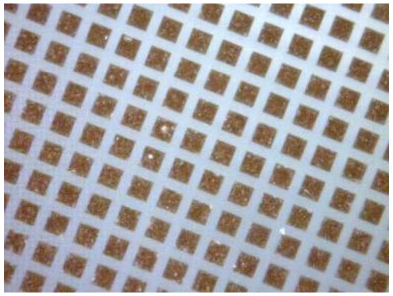
Array Fabrication

1-3 Piezocomposite is made from fragile PMN-PT piezocrystals

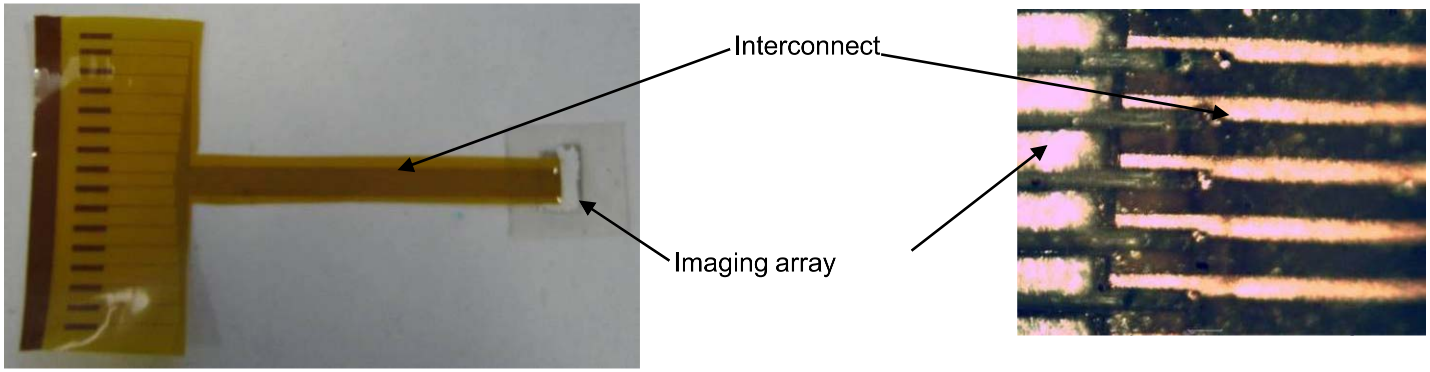
Composites made through dice and fill to enhance properties

Lapped and polished to a known thickness for the desired frequency

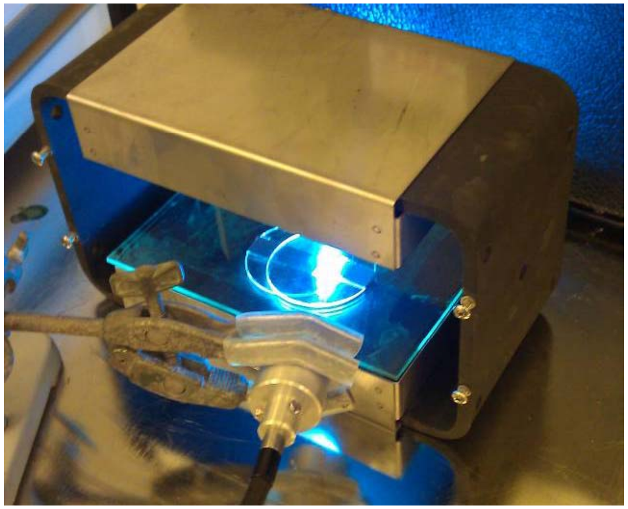
Matching and backing layers are cast on to avoid bondlines



1-3 piezocomposite



Bonding and Interconnects



Fragile PMN-PT materials need low temperature and pressure for bonding electrical interconnects

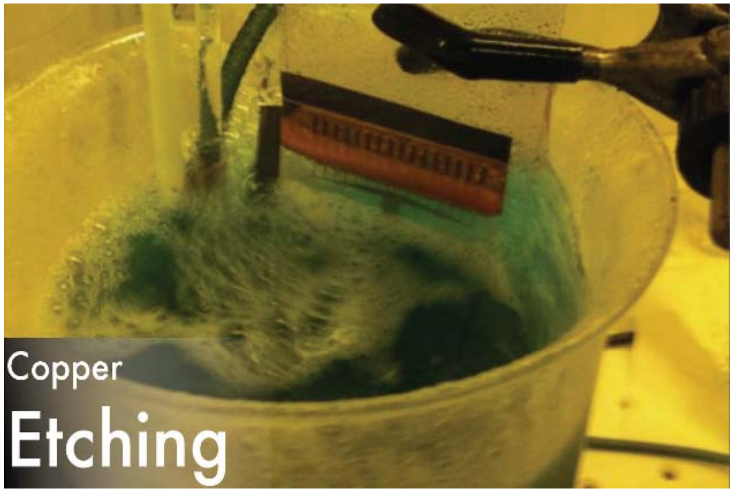
Conductive silver-loaded epoxy cures at room temperature

Electromagnetic anisotropic UV curable epoxy has a good potential

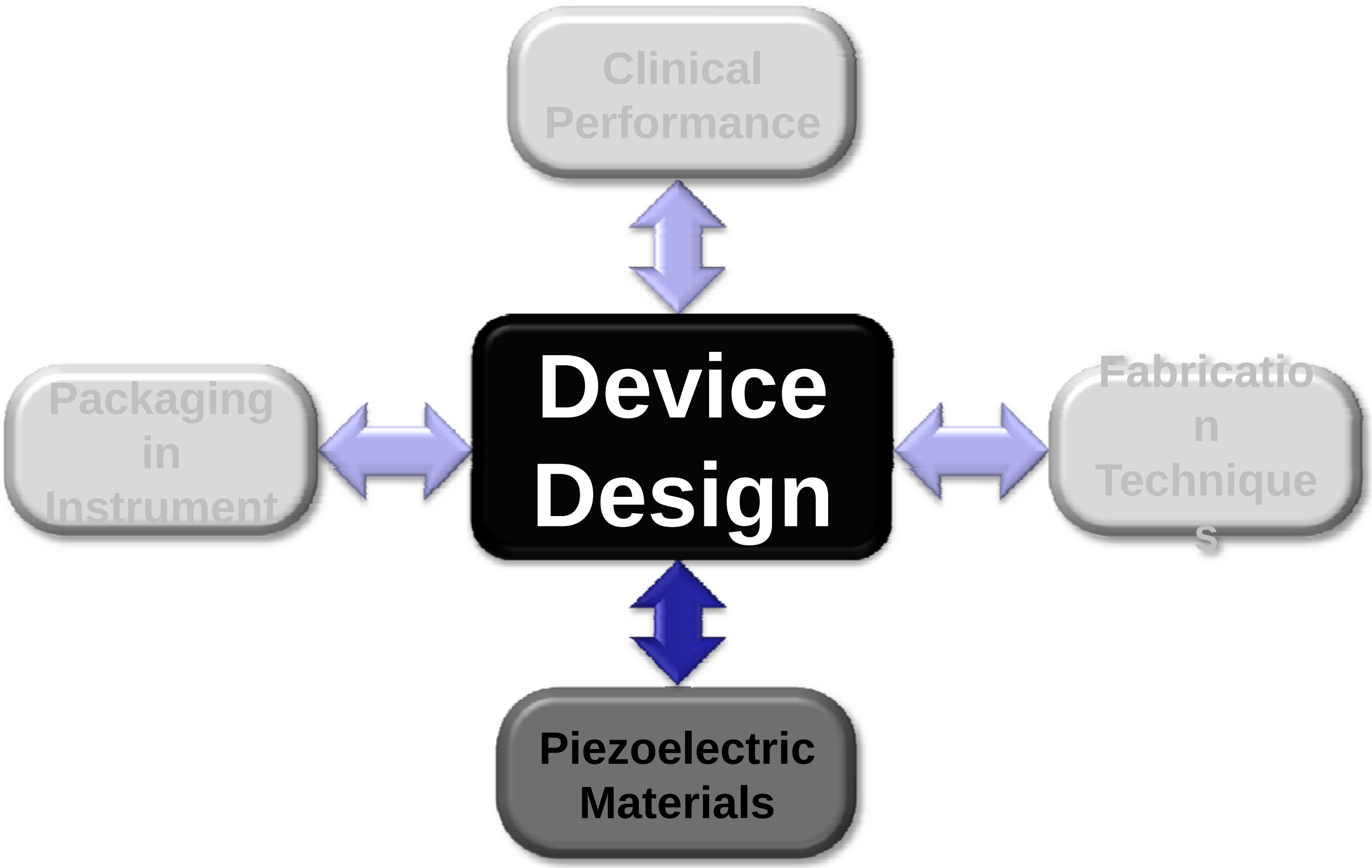
Photolithographic patterning of flex-circuit with dry film photoresist and copper etching

190 µm track width and 110 µm separation achieved as first prototype

Technique shows promising results for prototypes with finer pitch tracks



Single Crystal Piezoelectric Materials



PMN-PT Single crystal

Benefits

Improved properties compared to conventional ceramics

- For imaging
  - Improved coupling coefficient
  - High permittivity

Drawbacks

Fragile in fabrication

Expensive

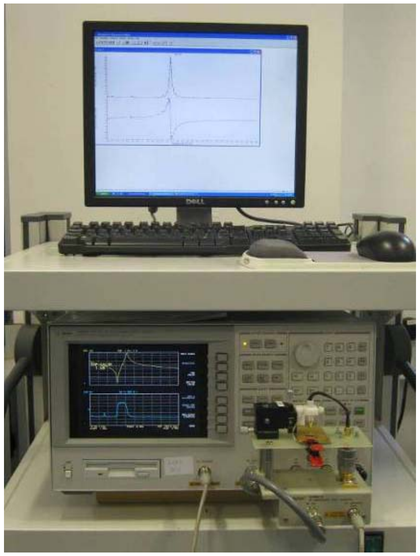
Difficult to characterise

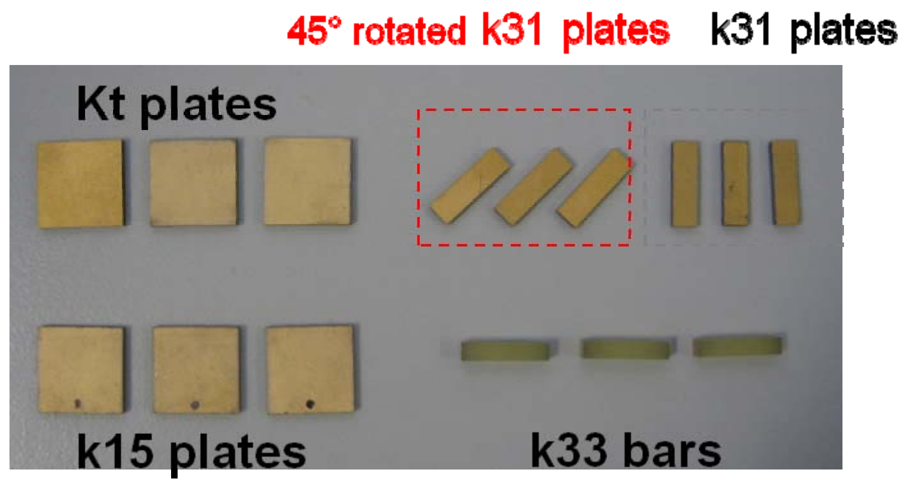
- Properties vary even if from the same batch

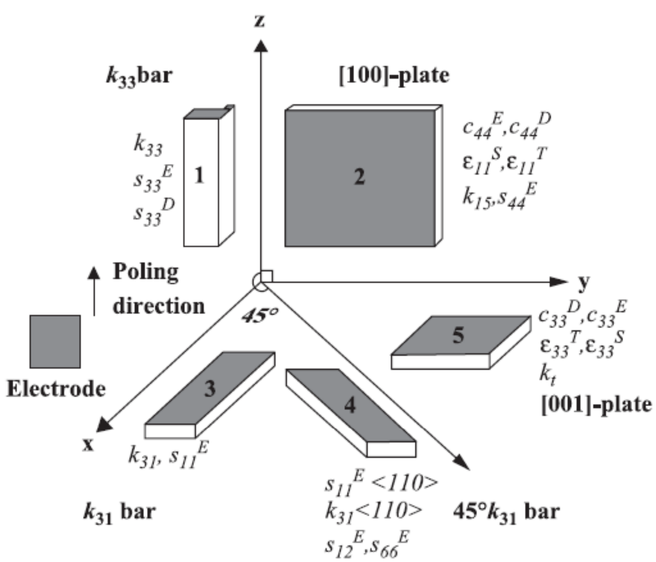
Makes modelling more challenging

Parameter	Symbol	PZT-5H	PMN-PT
Relative permittivity at constant strain	$\varepsilon^{s}33$	1470	3026
Electromechanical coupling coefficient	k_t	0.51	0.62
Curie temperature	T_c	195 °C	150 °C

Piezoelectric Material Characterisation



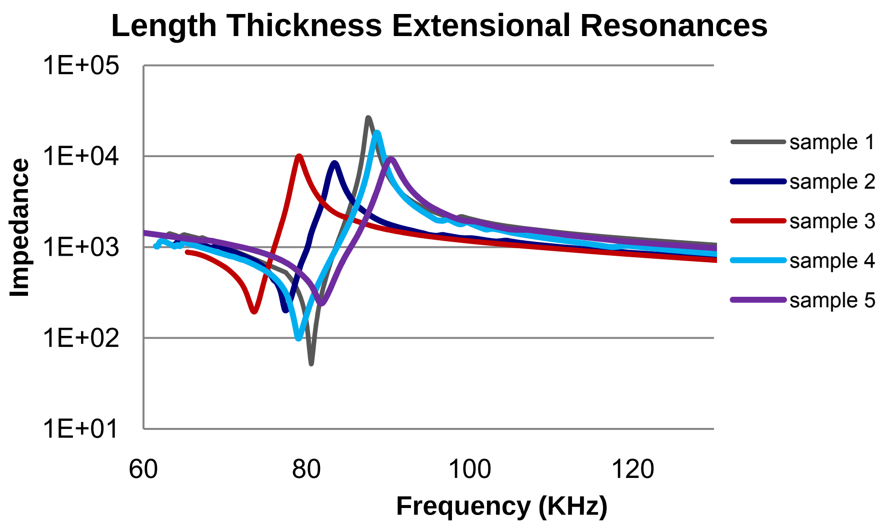


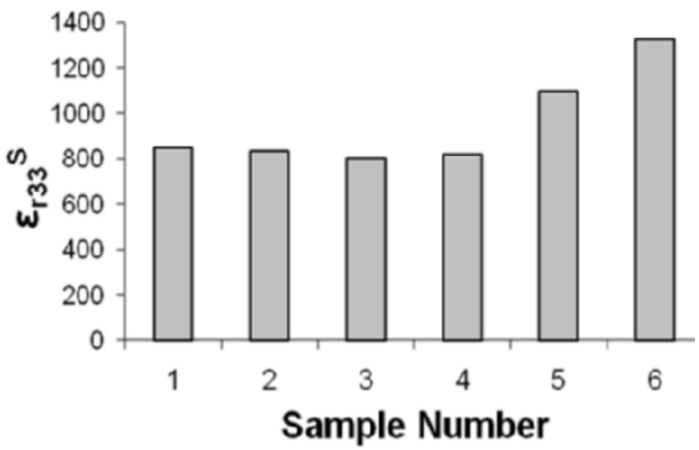


IEEE standard characterisation technique

- Multiple specimen geometries of plates and bars to isolate multiple resonant modes
- Electrical impedance spectroscopy of specimens analysed with PRAP (TASI Technical Software Inc., Kingston, Canada)
- Full set of elastic, piezoelectric and dielectric properties can be extracted

Uniformity of Material Properties





(a)

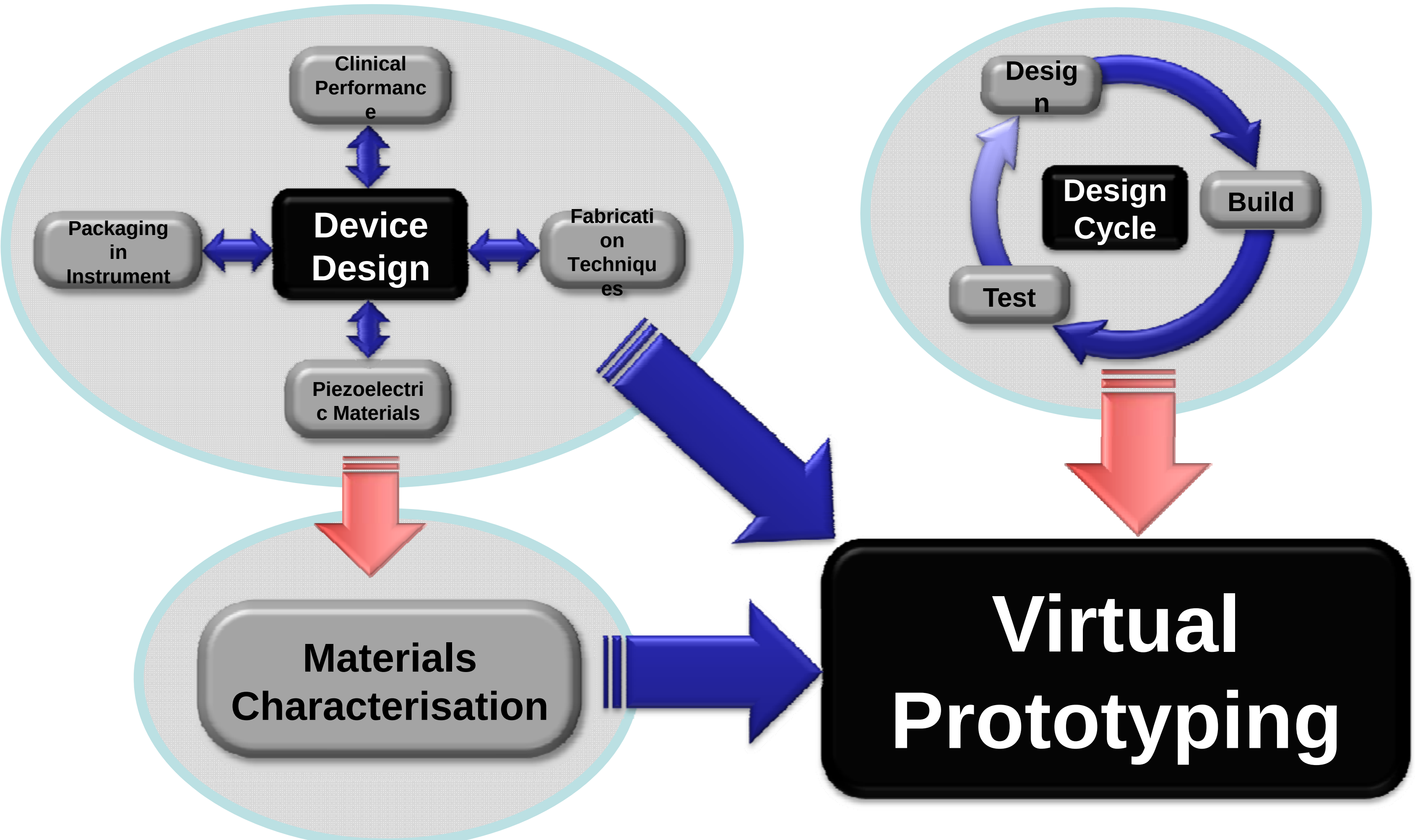
PMN-PT material from the same supplier

Varied material properties

For example relative permittivity at constant strain varies by ~80%

Z.Qui et al., "Characterisation of piezocrystals for practical configurations with temperature and pressure-dependent electrical impedance spectroscopy." IEEE Trans. Ultrason., Ferroelect. and Freq. Control, in press 2011.

Transducer Design
with Virtual Prototyping



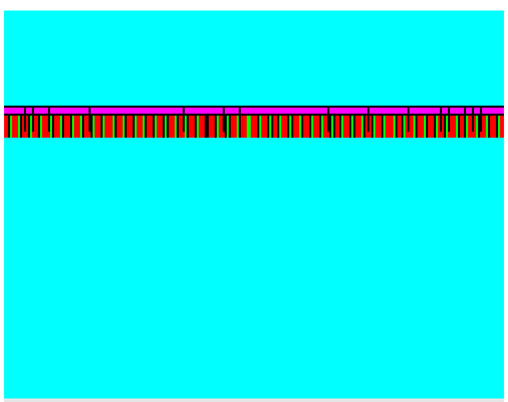
Virtual Prototyping

Finite element analysis (FEA) allows realistic and cost-effective analysis of device performance

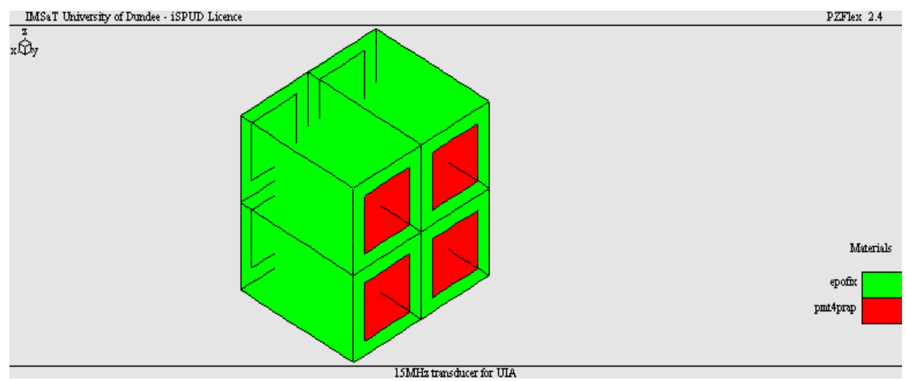
Virtual prototyping enables rapid testing of ranges of design parameters

PZFlex, a time domain FEA software utilised for the design

However, FEA requires accurate material properties for a realistic mode



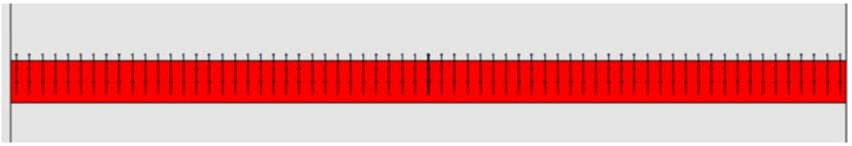
2D Composite with matching



3D Composite

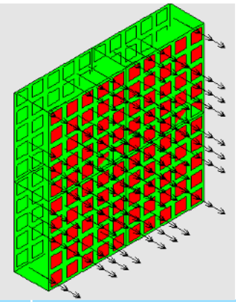
Virtual Prototyping

- First model:
  - Monolithic block of piezoelectric material
  - Material properties are modified to match simulation to experimentally obtained electrical impedance spectra
- Second model:
  - 1-3 piezocomposite block
  - Check electrical impedance from simulation and experiment match for confidence in full model
- Third model:
  - Full array with 1-3 composite, matching and backing layers
  - Can also model bond lines or electrode thicknesses to determine effects of fabrication processes
  - Used to optimise design



2D Block

2D Composite

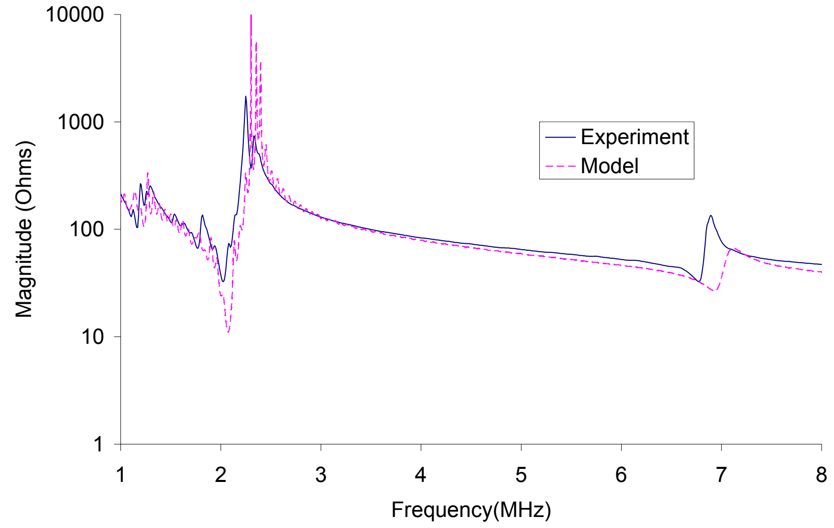


Preliminary Results: Model 1

The model was validated with a 2D plate resonating at low frequency

PTZ-5H (CTS 3203HD)

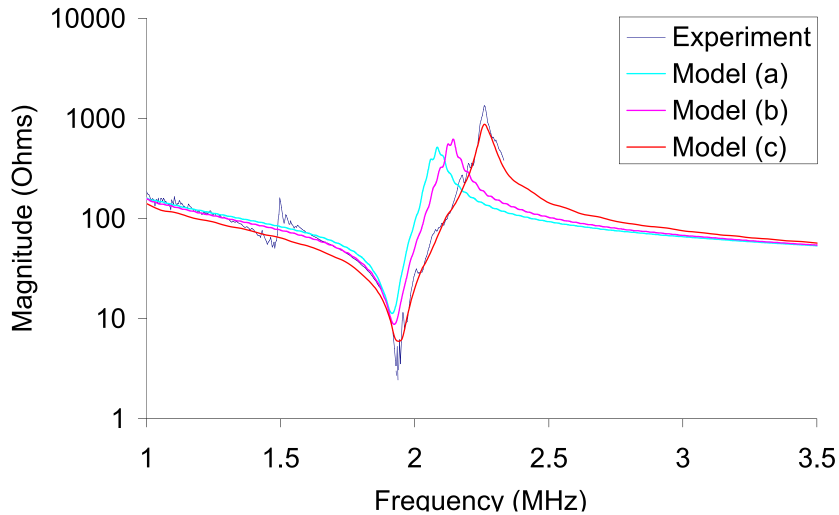
10x10x1 mm



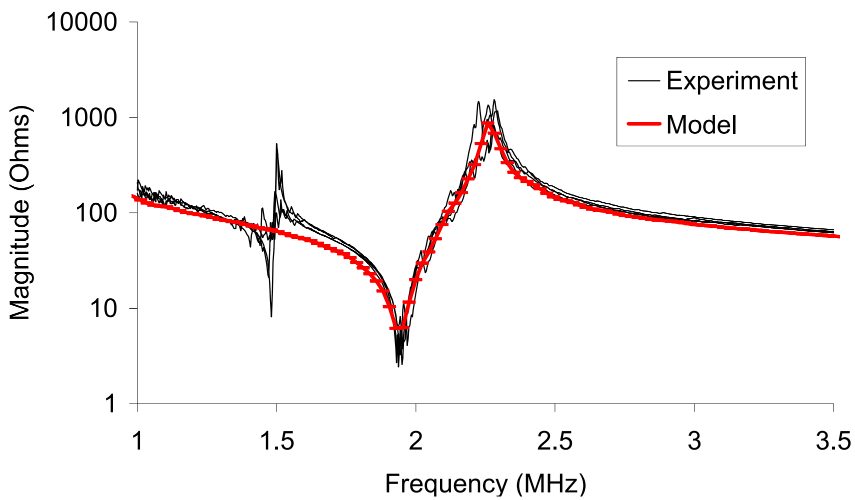
PMN-PT Model was more challenging to match to the experiment matches with experimental test

2D plate model was used to extract properties

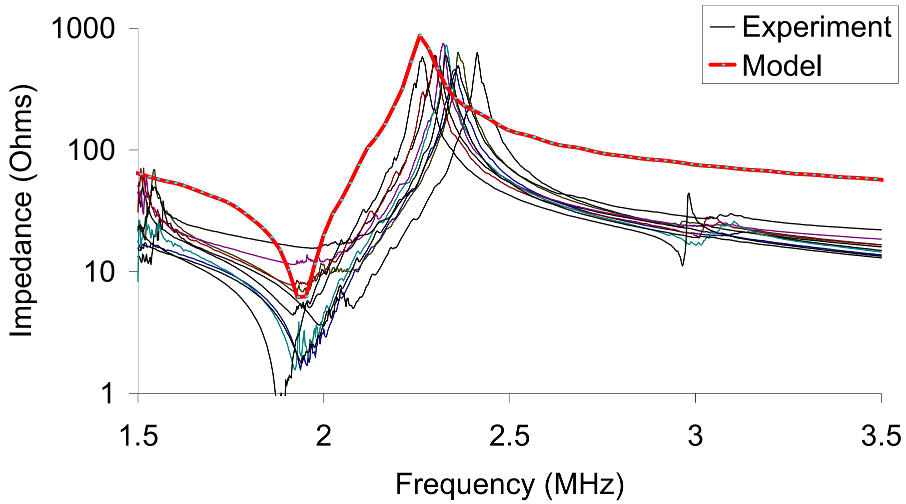
10x10x1 mm plate



Preliminary Results: Model 1



Supplier A



Supplier B

- It is more challenging to get a one model fits all for piezocrystal

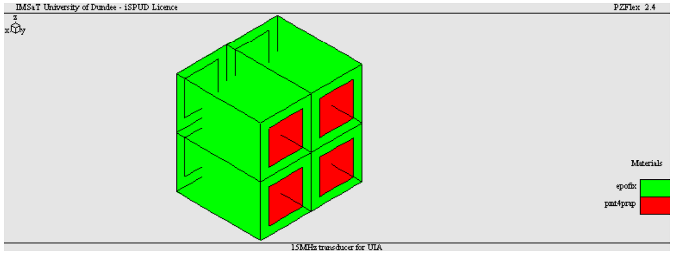
Preliminary Results: Model 2

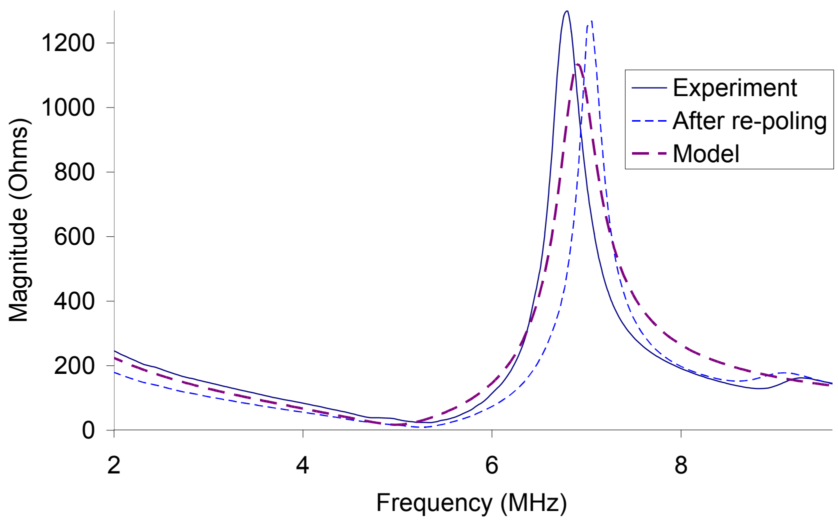
1-3 PMN-PT/Epoxy Composite

3d unit cell model

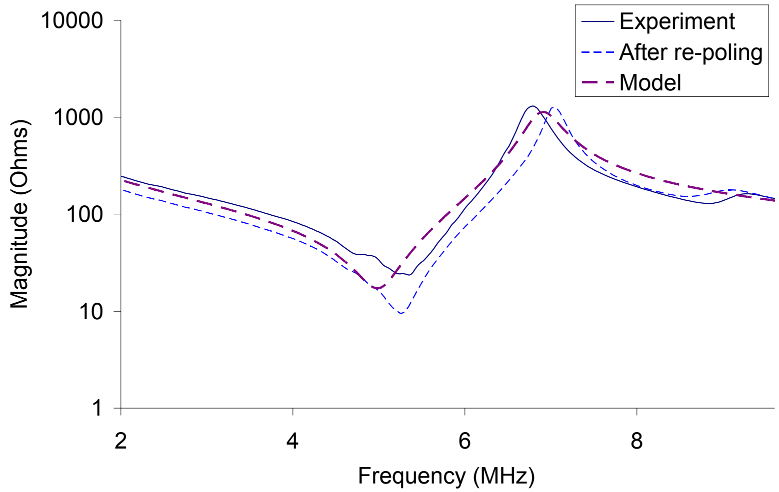
5 MHz resonant frequency

Some properties were increased by up to 80% to obtain a reasonable match



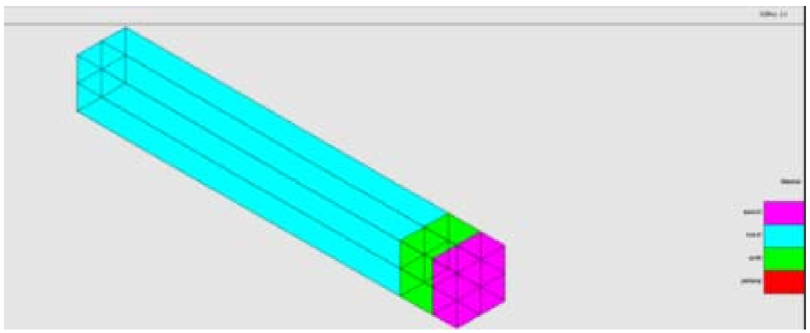


Fitted curves on linear scale

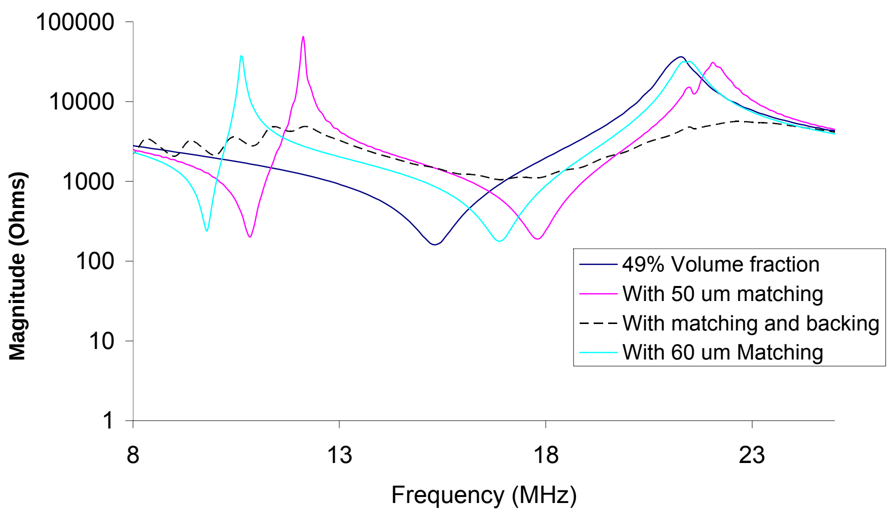


Fitted curve on log scale

15 MHz virtual prototyped transducer



- Active layer thickness is 80 µm
- Matching layer thickness is 50 µm
- Backing thickness is 800 µm



- 36% piezocrystal volume fraction in the composite has higher impedance magnitude at the electrical resonant frequency than the 49%.

Basic Fabricated Prototype

Single element transducer integrated into small tube

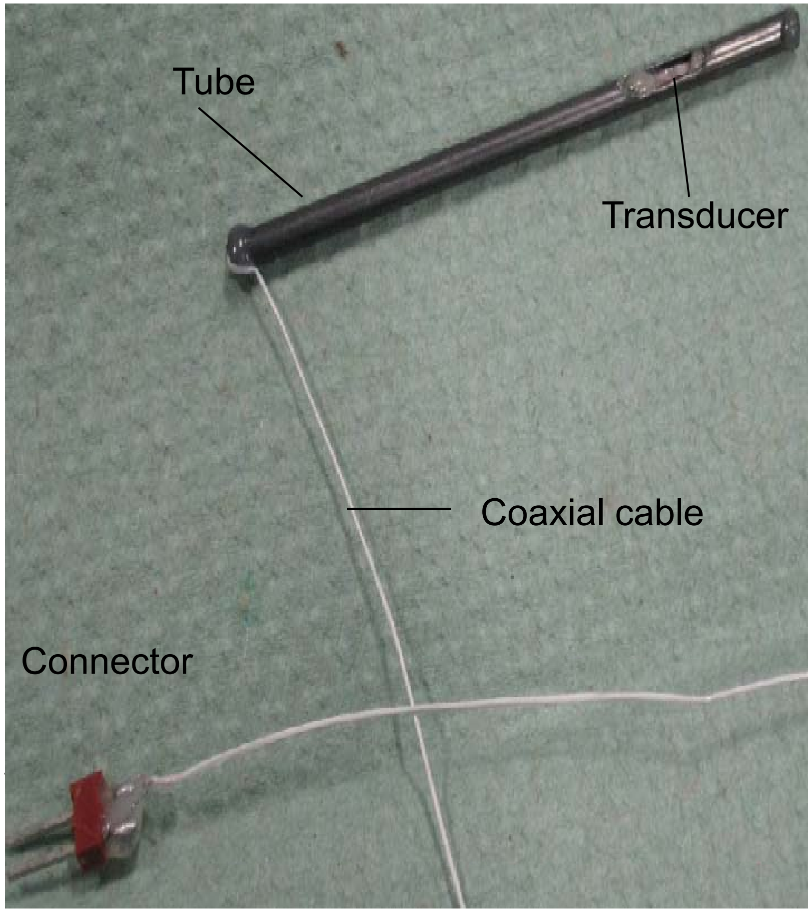
15 MHz transducer with matching and backing layers

Microfabrication techniques such as lapping and micro-dicing were used

Transducer element: 1 mm x 5 mm

Metal tube diameter: 2 mm

Coaxial cable diameter: 0.34 mm



Summary & Conclusions

High frequency transducers and arrays for **high resolution imaging** have significant clinical potential

- Miniature arrays enable integration with interventional tools
- Design of device and probe can optimised for specific applications

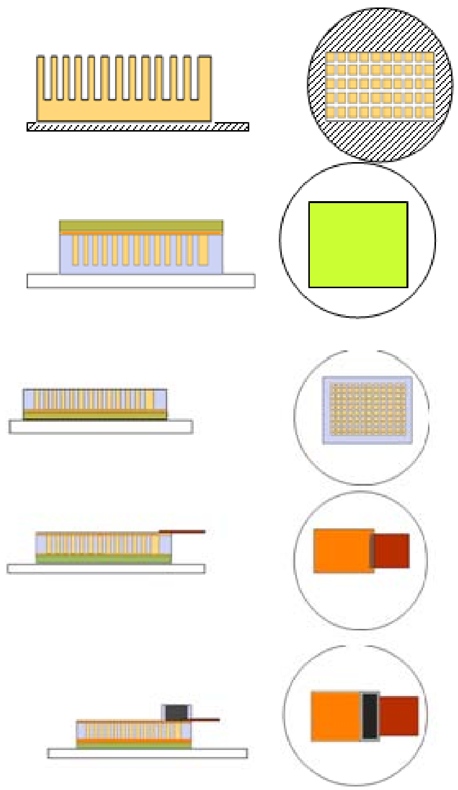
Fabrication of a prototype **array integrated into a biopsy needle** is in progress

Comprehensive **characterisation of single crystal piezoelectric materials** is required for more accurate results in virtual prototyping

Virtual prototyping is used to save time and expense in optimising the design of high frequency transducers

Further Work

- Prototype testing
  - Impedance analysis
  - Pulse-echo test
  - Imaging
- More material characterisation
- More device fabrication working through the process diagram
  - Fabrication of small pitch flexi-circuit
- Ex-vivo tissue testing



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Loadpoint Ltd. (Swindon, UK)

AFM Ltd. (Birmingham, UK)

Logitech Ltd. (Glasgow, UK)