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## 1 **Glass-windowed ultrasound transducers**

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### 19 **Abstract**

20 In research and industrial processes, it is increasingly common practice to combine  
21 multiple measurement modalities. Nevertheless, experimental tools that allow the co-  
22 linear combination of optical and ultrasonic transmission have rarely been reported.  
23 The aim of this study was to develop and characterise a water-matched ultrasound  
24 transducer architecture using standard components, with a central optical window  
25 larger than 10 mm in diameter allowing for optical transmission. The window can be  
26 used to place illumination or imaging apparatus such as light guides, miniature  
27 cameras, or microscope objectives, simplifying experimental setups.

28 Four design variations of a basic architecture were fabricated and characterised with  
29 the objective to assess whether the variations influence the acoustic output. The basic  
30 architecture consisted of a piezoelectric ring and a glass disc, with an aluminium  
31 casing. The designs differed in piezoelectric element dimensions: inner diameter,  
32 ID = 10 mm, outer diameter, OD = 25 mm, thickness, TH = 4 mm or ID = 20 mm,  
33 OD = 40 mm, TH = 5 mm; glass disc dimensions OD = 20 – 50 mm, TH = 2 – 4 mm;  
34 and details of assembly.

35 The transducers' frequency responses were characterised using electrical impedance  
36 spectroscopy and pulse-echo measurements, the acoustic propagation pattern using  
37 acoustic pressure field scans, the acoustic power output using radiation force balance  
38 measurements, and the acoustic pressure using a needle hydrophone. Depending on  
39 the design and piezoelectric element dimensions, the resonance frequency was in the  
40 range 350 – 630 kHz, the -6 dB bandwidth was in the range 87 - 97%, acoustic output  
41 power exceeded 1 W, and acoustic pressure exceeded 1 MPa peak-to-peak.

42 3D stress simulations were performed to predict the isostatic pressure required to  
43 induce material failure and 4D acoustic simulations. The pressure simulations  
44 indicated that specific design variations could sustain isostatic pressures up to  
45 4.8 MPa. The acoustic simulations were able to predict the behaviour of the fabricated  
46 devices. A total of 480 simulations, varying material dimensions (piezoelectric ring  
47 ID, glass disc diameter, glass thickness) and drive frequency indicated that the  
48 emitted acoustic profile varies nonlinearly with these parameters.

49

50

51

52 **Keywords:** ultrasound transducer, de-fouling, optical window, acoustic field  
53 simulation

54

## 55 **Introduction**

56

57 In research and industrial processes, it is increasingly common to combine multiple  
58 measurement modalities. Nevertheless, experimental tools that allow the co-linear  
59 combination of optical and ultrasonic transmission are rare [1]. Hence, the aim of this  
60 study was to develop and characterise a water-matched ultrasound transducer  
61 architecture, with a central optical window larger than 10 mm in diameter, which  
62 allows optical transmission.

63 Such a device could be used in research applications such as chemical dissolution,  
64 where the window would allow collinear optical spectroscopy [2], and flow metering  
65 [3], [4], where the optical window would allow illumination or imaging of flow and  
66 contamination using digital cameras. Adding ultrasound transmission elements to the  
67 optical examination port in a pipeline could prevent fouling by inducing inertial or  
68 stable cavitation [5], and allow Doppler based velocity measurements [6]. Adding an  
69 optical window in a single element ultrasound transducer creates a means to simplify  
70 experimental configurations by illuminating, imaging, or measuring through the  
71 ultrasound transducer.

72 To achieve simultaneous optical imaging and ultrasonic sonication or detection,  
73 several experimental configurations have previously been designed, such as applying  
74 ultrasound at obtuse angles and adding wave-guides to align optical and acoustic  
75 fields when visualising ultrasonic effects using microscopes [7]–[11]. However, these  
76 configurations require time-consuming alignment techniques and changes in drive  
77 frequency or number of pulses requires re-alignment with the optical field. A  
78 transducer design allowing trans- and co-linear optical visualisation in the acoustic  
79 propagation direction would reduce complexity and provide possibilities for new  
80 experimental configuration for research and industrial applications.

81 Previously, only one type of optically transparent ultrasound transducer has been  
82 reported, to our knowledge. This design is based on lithium niobate (LNO) crystals  
83 coated with transparent indium tin oxide (ITO) electrodes with resonance frequencies  
84 of 6.3 and 7.1 MHz [1]. The device has no case or backing and is intended for use in  
85 particle manipulation in microfluidic devices, producing output pressures of up to  
86 0.5 MPa. The ~600 nm thick ITO electrodes affected the optical transmittance  
87 resulting in non-linear wavelength-dependent transmission. The electrodes are also  
88 susceptible to chemical and contact damage, and do not work under isostatic pressures  
89 surpassing 110 MPa [12]. Furthermore, ITO deposition is more complicated and  
90 costly than more common electrode coatings such as conductive silver paint or  
91 vacuum-deposited gold.

92 Here, an ultrasound transducer architecture is presented, and four design variations  
93 based on it, with a circular optical window with diameter 10 or 20 mm, where the  
94 piezoelectric element is encased within the device. The fabrication procedure is  
95 described for all the designs. Their frequency responses were characterised using  
96 electrical impedance spectroscopy and pulse-echo measurements, the acoustic  
97 propagation pattern using acoustic pressure field scans, the acoustic power output  
98 using radiation force balance measurements, and the acoustic pressure output using a  
99 needle hydrophone. 3D stress simulations were also performed to predict the isostatic

100 pressure required to induce material failure and 4D acoustic simulations to assess the  
101 possibility to simulate and hence optimise the transducer response.

102

## 103 **1.0 Materials and Methods**

104

105 The design criterion of the device was to allow the insertion of optical devices such as  
106 microscope objectives with long working distances ( $> 10$  mm), small-aperture  
107 cameras such as endoscopic cameras, and fibre or liquid light guides into the  
108 transducer to image or illuminate the test medium through the optical window. Based  
109 on in-house hardware and experimental configurations, the minimum required  
110 window size was determined to be more than 10 mm in diameter and the maximum  
111 device diameter to be approximately 70 mm. The acoustic requirements were for the  
112 point of highest acoustic pressure to be located collinearly with the centre of the  
113 optical window between 0 – 40 mm from the surface of the device; for a bandwidth of  
114  $> 60\%$  to allow a single device to operate at multiple frequencies; and for acoustic  
115 pressure output to exceed 1 MPa. The device was also required to sustain as high an  
116 isostatic pressure as possible for operation in oil and gas pipes. Furthermore, it should  
117 consist of commercially available “off-the-shelf” components that would not require  
118 specialised modification, allowing any research or industry laboratory to manufacture  
119 such a device.

120

## 121 **1.2 Design**

122 An architecture consisting of as few components as possible, with adhesive joining,  
123 was chosen to reduce complexity and manufacturing costs. It was based on  
124 conventional single-element ultrasound transducer architecture [13], [14]. The  
125 changes made were to use a piezoelectric ring to replace the piezoelectric disc and to  
126 add a glass disc. This architecture was chosen as it involves only geometric shapes  
127 *i.e.*, discs, rings, and cylinders, that can be purchased commercially and aligned easily  
128 during assembly without specialised hardware.

129 Four designs were evaluated to determine the effect of geometry differences on the  
130 acoustic output and mechanical strength. Graphical renderings and cross-sections of  
131 the designs can be seen in **Figure 1A**. **Figure 1B** shows the parameters that can be  
132 varied using this construction whilst **Table 1** provides the dimensions used in the  
133 prototype transducers. The outer diameters (ODs) and inner diameters (IDs) of the  
134 piezoelectric discs were, respectively, 40 mm and 20 mm for two of the designs, and  
135 25 mm and 10 mm for the other two designs. Including the adhesive and case, this  
136 resulted in assembled device outer diameters of, respectively, 50 mm and 38 mm.

137 For this architecture the chosen piezoelectric material was PZ54 (Meggit Sensing  
138 Systems: Ferroperm Piezoceramics, Kvistgaard, Denmark) due to its low cost,  
139 €11 - 14 per ring and commercial availability; high mechanical quality factor,  
140  $Q_m > 1500$ ; relatively high piezoelectric charge coefficient,  $d_{33} = 500 \times 10^{-12}$  C/N; and  
141 acceptable maximum operating temperature,  $T = 130^\circ\text{C}$ . Theoretically, the acoustic  
142 impedance of the piezoelectric material would allow the glass disc to act as an  
143 acoustic impedance matching layer for acoustic propagation into water.

144 Based on the theoretical acoustic impedances of the materials,  $Z_{\text{PZT}} \approx 33$  MRayl and  
145  $Z_{\text{water}} \approx 1.5$  MRayl, the optimum acoustic impedance of the matching layer is 7.0  
146 MRayl. The acoustic impedance of quartz glass is in the range 10 – 15 MRayl, higher  
147 than the required value, but still of benefit in increasing the acoustic transmission into  
148 water from 17% to 30%.  $Q_m > 1500$  indicates low internal damping in the  
149 piezoceramic, reducing internal heating and allowing long pulse durations. The

150 piezoelectric charge coefficient was one of the highest in comparison to other  
151 available materials with the required value of  $Q_m$ .  
152 Optical grade synthetic fused quartz discs ( $\text{SiCl}_4$ ) (H. Baumbach & Co. Ltd, Ipswich,  
153 United Kingdom) were used as the glass discs for all transducers.  
154 Based on the thickness of the piezoelectric rings, their theoretical centre frequencies  
155 were  $f_c = 400\text{ kHz}$  for 5 mm thick elements and  $f_c = 500\text{ kHz}$  for 4 mm thick elements.  
156 Using these parameters the ideal glass thickness, based on  $\frac{1}{4}\lambda$  estimation [13], is  
157 3.4 mm at 400 kHz, and 2.75 mm at 500 kHz. In the prototypes, the closest  
158 thicknesses available practically were used.  
159 Design 1 consisted of the 40-mm OD PZ54 ring and the thinnest (TH = 2 mm) and  
160 largest diameter (50 mm) glass disc, which was bonded directly to the top of the  
161 aluminium transducer casing. The glass was 1.4 mm thinner (41% lower) than the  
162 theoretical optimum thickness. Design 2 had the thickest glass plate (TH = 4 mm)  
163 with a diameter equal to the PZ54 ring (OD = 40 mm). In this design the glass was  
164 bonded to the PZT ring within the casing. The glass was 0.6 mm thicker (18% higher)  
165 than the ideal thickness. Designs 3 and 4 consisted of 25-mm OD PZT elements and  
166 both used 3 mm thick glass discs. The glass thickness was 0.25mm thicker (9%  
167 higher) than the theoretical optimum. The diameter of the glass disc in Design 3 was  
168 the same as the PZ54 ring (OD = 25 mm). Design 4 used a 30 mm diameter glass  
169 disc, 5mm larger than the OD of the PZ54.  
170 These variables were chosen to evaluate the effect of design variations on the acoustic  
171 output and mechanical strength.

172  
173

### 174 1.3 Construction

175 Designs 2 – 4 used identical construction processes, whereas Design 1 required a  
176 revised order of construction to allow glass bonding to the outer edge of the  
177 aluminium case.

178 **Figure 2** shows the steps used to construct the devices. Designs 2 – 4 were  
179 constructed as follows. The central hole of a PZ54 ring was filled by hand with  
180 modelling clay (Dream Dough™, Sense Försäljning AB, Jordbro, Sweden) (**Fig. 2A**)  
181 to prevent epoxy seepage onto the corresponding glass area during the later stages of  
182 assembly. The hole was filled with clay by initially placing the PZ54 ring on a flat  
183 surface, then pushing and compressing the clay into the hole with the thumb until no  
184 volume change was observed and the entire volume of the PZ54 ring hole was full.  
185 The ring was then removed from the flat surface and held by the outer circumference  
186 and excess clay was added to the upper side of the hole and gently forced downwards  
187 allowing a small dimple (~3 mm dome) to protrude from the bottom of the ring. The  
188 upper surface was left unmodified. This ensured complete hole coverage when the  
189 PZ54 ring was bonded to the glass disc.

190 EpoFix epoxy (Struers A/S, Ballerup, Denmark) was prepared according to the  
191 manufacturer's instructions and was degassed in a disposable plastic beaker by  
192 cycling between 500 Pa and 0.1 MPa with 30 second waits at each pressure.  
193 Degassing was complete when no more air bubbles were observed at 500 Pa,  
194 requiring 10 – 15 cycles. The degassed epoxy was poured into the central body of a  
195 5 mL Omnifix Solo® syringe (B.Braun Melsungen AG, Melsungen, Germany) by  
196 removing the injection piston and placing a finger on the exit port to prevent seepage.  
197 The epoxy was poured ensuring continuous surface contact from the degassing beaker  
198 to the syringe body. A total of ~5mL was poured into the syringe to avoid a large  
199 headspace. The injection piston was then placed back into the main body and a 21

200 gauge, 2.54 cm long Sterican<sup>®</sup> needle (B.Braun Melsungen AG, op. cit.) was placed  
201 over the injection nozzle.

202 The epoxy was injected onto the glass disc, placed on a glass working-surface, whilst  
203 avoiding contact between the needle and glass disc. The epoxy was injected as a  
204 continuous single ring approximately 2 mm wide concentrically aligned with the  
205 middle of the corresponding PZ54 ring location, *i.e.*, with a diameter of 30 mm for  
206 Design 2, and 15 mm for Designs 3 and 4 (**Fig. 2B**). The PZ54 ring was placed on  
207 the glass disc ensuring the lower dome of the modelling clay contacted the centre of  
208 the disc first. Once in contact, the PZ54 ring and clay were uniformly pressed onto the  
209 glass. Proper contact was continuously observed through the glass working surface.  
210 Air pockets between the PZ54 ring and glass surface were removed by applying  
211 pressure on the PZ54 ring above them and observing the distribution of epoxy through  
212 the glass working-surface. Once homogenous epoxy spread and contact was achieved  
213 a 2 kg weight was placed on the PZ54 ring and the assembly was left for the epoxy to  
214 cure at room temperature for 24 h.

215 Once curing was complete, the modelling clay was removed by hand. Because of the  
216 oil content of the modelling clay, the epoxy did not bond fully to it. Residual  
217 modelling clay that had partially bonded to the epoxy was removed using a scalpel  
218 whilst avoiding damage to the glass disc. Excess epoxy between the PZ54 ring OD  
219 and the glass disc was removed in a region of width 2 mm using a scalpel and  
220 scraping action to expose the edge of the electrode. Conductive access to this  
221 electrode between the glass and the PZ54 ring was checked using a multimeter. A  
222 resistance of 0  $\Omega$  was targeted. The entire stack was then cleaned using isopropyl  
223 alcohol (IPA, C<sub>3</sub>H<sub>8</sub>O) to remove residual oil left behind on the glass from the  
224 modelling clay.

225 A 3-cm long, micro-coaxial cable (CXA3607-50, Piezo-Metrics, Inc., St. George,  
226 Utah, USA) was glued to the edge of the surface electrodes using silver-loaded epoxy  
227 (Elektron Technology, Cambridge, United Kingdom) and the PZ54 - glass stack was  
228 placed in an oven at 100°C for 15 min to cure the silver-loaded epoxy and attain  
229 maximum conductivity (**Fig. 2C**). The stack was left for 2 hr to cool to room  
230 temperature before proceeding. The exposed end of the micro-coaxial was spliced and  
231 soldered to a 30-cm long coaxial cable of larger diameter (RG178PE, RS  
232 Components, Corby, Northants, United Kingdom).

233 Next, the PZ54 - glass stack was placed on adhesive UV-release tape (Adwill D-202,  
234 Lintec Corporation, Tokyo, Japan), glass-side down, ensuring no gaps or air pockets  
235 were visible between the tape and glass surface. An aluminium cylinder was  
236 concentrically aligned around the stack ensuring no contact between the stack and  
237 cylinder. A 2 mm diameter hole was drilled into the cylinder wall for cable routing  
238 (**Fig. 2D**). The UV tape ensured that the front face of the aluminium case and the  
239 piezoelectric-glass disc remained aligned and that the Epofix epoxy that was added  
240 (**Fig. 2E**) did not seep out or on to the glass surface. The PZ54 - glass stack was  
241 bonded to the case using Epofix epoxy (prepared as previously described) by filling  
242 the gap between the case and PZ54 - glass stack up to the upper surface of the stack  
243 and left to cure for 24 hr. The tape was removed by exposing it to UV light at 365 nm  
244 wavelength (UPV PL Handheld, Company Seven, Montpelier, MD, USA) for 10 min.  
245 In the last step, the RG178PE cable was threaded through the 2 mm hole and a BNC  
246 connector was attached to the end of the cable. The gap between the case and  
247 RG178PE cable was sealed with 5-minute epoxy (Unibond Super Epoxy, Henkel AG  
248 & Co. KGaA, Düsseldorf, Germany) and the back of the case was closed off using a  
249 poly(methyl methacrylate) disc (PMMA) bonded in place with 5-minute epoxy

250 (Unibond Super Epoxy, op. cit.). **Figure 2F** shows a photograph of a completed  
251 device.

252 Design 1 was built using the same steps but with small changes to ensure better  
253 alignment and adhesion due to the larger diameter of the glass disc. First, the micro-  
254 coaxial / RG178PE cable combination was bonded onto the edges of the upper and  
255 lower electrodes. The PZ54 ring, without the glass disc, was placed on UV-release  
256 tape (Adwill D-202, op. cit.), bonded to the case, and left to cure for 24 hr at room  
257 temperature (**Fig. 2C – E**). The UV tape was removed and the hole in the middle of  
258 the ring was sealed with modelling clay. The glass was bonded in place (**Fig. 2A – B**)  
259 using the techniques previously described.

260

## 261 **1.4 Characterisation**

### 262 **1.4.1 Frequency Characterisation**

263 Frequency characterisation was performed to determine the electrical efficiency of the  
264 transducers and their operating frequencies. The frequency response of the  
265 transducers was characterised using electrical impedance spectroscopy and pulse-echo  
266 measurements. Electrical impedance spectroscopy was performed using an  
267 impedance analyser (4294A, Agilent Technologies/Keysight, Santa Clara, CA, USA)  
268 with a 50-Ω source impedance. During measurement, the transducers were immersed  
269 in a 500-ml beaker filled with de-gassed water. The acoustic propagation direction  
270 was towards the bottom of the beaker. The transducer was clamped in place using an  
271 electrically insulated clamp contacting the aluminium case. The transducer was placed  
272 approximately 8 cm from the bottom of the beaker. A 10 mm thick ultrasound-  
273 absorbing disc (Aptflex F48, Precision Acoustics Ltd, Dorchester, Dorset, United  
274 Kingdom) was placed at the bottom of the beaker to prevent acoustic reflections  
275 interfering with the electrical impedance measurements. The echo reduction was  
276 ~40 dB.

277 The electrical reflection coefficient magnitude ( $\delta$ ) was calculated using:

$$278 \quad d = \sqrt{\left(\frac{R^2 - Z_0^2 + X^2}{(R + Z_0)^2 + X^2}\right)^2 + \left(\frac{2Z_0X}{(R + Z_0)^2 + X^2}\right)^2}, \quad (\text{Eq. 1})$$

279 where  $Z_0$  is the source impedance, and  $R$  and  $X$  are the measured electrical resistance  
280 and reactance, respectively.  $\delta = 1$  is equivalent to 100% electrical reflection and  $\delta = 0$   
281 is equivalent to 0% electrical reflection, hence perfect electrical impedance matching  
282 to the 50 Ω resistance of the driving source. The reflection coefficient magnitude  
283 spectrum has been shown to be a good indicator of transducer peak frequency,  $f_p$ ,  
284 bandwidth,  $BW_f$ , and acoustic efficiency with frequency [15].

285 Based on the ASTM guidelines [16], the pulse-echo method was used to determine  
286 the working frequency and bandwidth of the ultrasound transducer *in situ*. This data  
287 was compared to the electrical impedance measurements. The transducer was placed  
288 in a 220 l water bath facing a stainless steel plate of thickness 20 mm, equivalent to  
289  $1.4\lambda$  at 400 kHz, positioned 20 cm away from the surface of the ultrasound  
290 transducer. The stainless steel plate acted as an acoustic reflector, reflecting ~88% of  
291 the transmitted energy, based on the acoustic impedance between it and water [17].  
292 The device was driven by a 10 V<sub>pp</sub>, 5-cycle burst sine wave with a 5 ms pulse  
293 repetition period generated by a waveform generator (33500B, Agilent  
294 Technologies/Keysight), and connected in parallel to an oscilloscope (WaveJet 354a,  
295 Teledyne LeCroy SA, Geneva, Switzerland) which was used to monitor the amplitude  
296 of the drive signal and which did not provide any additional loading. A total of five

297 cycles was chosen as this was the minimum number required to reach the maximum  
 298 peak-to-peak pressure in the transient wave for a given drive voltage.  
 299 The peak-to-peak amplitude of the echo was measured at drive frequencies in the  
 300 range 0.1 – 1.0 MHz with 1000 samples, yielding a step size of 1 kHz. Based on these  
 301 results the following equations were used to determine the bandwidth ( $BW$ ), centre  
 302 frequency ( $f_c$ ), and the mechanical quality factor ( $Q_m$ ):  
 303

$$\begin{aligned}
 BW_f[\text{kHz}] &= f_u - f_l \\
 BW_{\%} &= \frac{BW_f}{f_c} \times 100 \\
 f_c &= \frac{f_u + f_l}{2} \\
 Q_m &= \frac{BW}{f_p}
 \end{aligned}
 \tag{Eq. 2}$$

305 where  $f_u$  and  $f_l$  are the -6 dB upper and lower frequency cut-offs.  $f_p$  was  
 306 determined as the frequency of highest acoustic echo amplitude.  
 307

#### 308 **1.4.2 Acoustic pressure field characterisation**

309  
 310 Acoustic pressure field characterisation was performed to determine the location and  
 311 dimensions of the acoustic maxima. The acoustic pressure field was characterised  
 312 using a custom made 220 l ultrasound characterisation tank with dimensions 500 mm  
 313  $\times$  980 mm  $\times$  450 mm based on three orthogonally mounted linear stages. A PVDF  
 314 needle hydrophone (Precision Acoustics Ltd, op. cit.) with an effective diameter of  
 315 200- $\mu$ m connected to a submersible pre-amplifier (HP series, Precision Acoustics Ltd.  
 316 op. cit.) was used to sample the acoustic pressure in 4D ( $x$ -,  $y$ -,  $z$ - axis, and time)  
 317 with a spatial sampling step of 500  $\mu$ m. This resulted in a sampling step size between  
 318 1.19 – 2.14 $\times$  the operating wavelength. The transducers were driven at their resonance  
 319 frequencies ( $f_p$ ) using a 1  $V_{pp}$ , 5-cycle burst sine wave with a 1 ms pulse repetition  
 320 duration via the 33500B waveform generator connected to a 200 W linear class-A  
 321 power amplifier with 53 dB gain (PA200-12, Precision Acoustics Ltd., op. cit.)  
 322 through a -20 dB attenuator. The peak-to-peak voltage,  $V_{pp}$ , was then mapped in 2D  
 323 to determine the acoustic pressure field. For each transducer, three 2D scans were  
 324 performed, one across the centre of the transducer in the propagation plane axis, one  
 325 cross section performed  $< 1$  mm from the face of the transducer, and one normal cross  
 326 section at the distance of highest peak-to-peak pressure.  
 327

#### 328 **1.4.3 Acoustic power and pressure measurements**

329 Acoustic power measurements were performed to compare the power output of the  
 330 design variations. The power output was measured with a bespoke radiation force  
 331 balance, based on the IEC 61161 standard [18]. The radiation force balance  
 332 configuration is valid for frequencies in the range 0.5 – 25 MHz and acoustic power  
 333 up to 1 W. The transducers were driven using a continuous wave at their peak  
 334 frequencies,  $f_p$ , via the combination of the 33500B waveform generator and PA200-12  
 335 power amplifier. The transducer was positioned radiating downwards in degassed  
 336 water towards a 10mm thick acoustic absorber (Aptflex F28, Precision Acoustics



337 Ltd., op. cit.), attached to a high-precision balance (SE300D, VWR International,  
338 Radnor, PA, USA). Acoustic power was calculated using:

339  
340 
$$P = c \times m \times g, \quad (\text{Eq. 3})$$

341 where  $c$  is the speed of sound in the propagating media,  $m$  is the measured mass,  
342 and  $g$  is the gravitational constant. To compensate for thermal and other drifts,  
343 extrapolated on and off balance readings were performed [19]. The transducer was  
344 turned on and off sequentially for 20 seconds, five times. Specifically, the  
345 measurement was started at time  $T = 0$  s with 20 s off time. The transducer was then  
346 powered on from  $T = 20$  s to  $T = 40$  s. A complete, single measurement took 200 s.  
347 Linear extrapolation was performed following UK National Physics Laboratory  
348 guidelines [20]. Using the first 40 s as an example, the extrapolated acoustic power,  
349  $P_{ex}$ , was calculated by:

351  
352 
$$P_{ex} = P_{T_{40s}} - 2 \times (P_{T_{40s}} - P_{T_{30s}}) - P_{T_{20s}}, \quad (\text{Eq. 4})$$

353 where  $P_{T_{XXs}}$  is the power at a given time (XXs) from the start of the measurement.  
354 Each measurement was repeated 5 times.

355 Acoustic pressures were calculated using the mean value of  $P_{ex}$  and the full width at  
356 half maximum (FWHM) area,  $A_{FWHM}$ , from the field scan performed in the focus of  
357 the transducers using the equation:

358  
359  
360 
$$p = \sqrt{\frac{P r_0 c_{dw}}{A_{FWHM}}}, \quad (\text{Eq. 5})$$

361 where  $r_0$  and  $c_{dw}$  are the density and speed of sound of distilled water, respectively.  
362

363 To validate the results, each transducer was placed in the calibration tank and driven  
364 using a 5-cycle burst sine wave with a 1 ms pulse repetition duration at the  
365 transducer's frequency of peak output via the 33500B and PA200-12 combination. A  
366 calibrated PVDF needle hydrophone (Precision Acoustics, Ltd., op. cit.) was  
367 positioned at the acoustic focus, its 1-mm diameter being 38.0% of the wavelength of  
368 2.63 mm at the maximum frequency under investigation. Then the waveform  
369 generator voltage output was increased incrementally from 0.1 V<sub>pp</sub> to 5.0 V<sub>pp</sub> in  
370 0.2 V<sub>pp</sub> steps and the peak-to-peak acoustic pressure was recorded.  
371

#### 372 373 **1.4.5 Thermal measurements** 374

375 Thermal measurements were performed to determine if the acoustic output of the  
376 architecture and the specific designs based on it was limited by heating of the PZ54  
377 element. Heating was evaluated by placing the devices in the 220 l water-tank and  
378 driving them at 1 W acoustic output power for 60 s using a continuous wave at their  
379 respective values of  $f_p$  using the 33500B and PA200-12 combination. Afterwards, the  
380 transducers were immediately removed from the water-tank, dried using a paper towel  
381 in a process taking no more than 2 s, and the entire surface of each transducer case  
382 and glass disks was scanned using an infrared temperature gauge (Art. No.: 36-5737,

383 Clas Ohlson, Oslo, Norway). The maximum temperature of the case and glass disc  
384 was recorded. The process was repeated 5 times following a wait period of ~30 min  
385 between each measurement allowing the transducer maximum surface temperature to  
386 fall to room temperature.

387

## 388 **2 Simulations**

389

### 390 *2.1 Acoustic pressure field simulations*

391

392 The acoustic fields were simulated using the PZFlex 2014 finite element analysis  
393 (FEA) software package (Thornton Tomasetti, New York, NY, USA) on a multicore  
394 Windows Xeon-based workstation. This package was selected because the authors  
395 have previous experience with it. An axisymmetric model with circular symmetry was  
396 used to produce 4D results. All material properties required were already available  
397 within the standard software library. Element size was set at 1/50<sup>th</sup> of the driving  
398 frequency wavelength. Multi-parametric simulations were performed using Design 4  
399 as the base architecture. The PZ54 ring centre hole diameter, glass thickness, glass  
400 diameter, and drive frequency were varied to determine if these changes resulted in a  
401 trend toward higher acoustic pressures.

402 For each modified variable, all other design parameters remained constant using the  
403 values stated in **Table 1**. The range of variables and their respective step size are  
404 shown in **Table 3**. The transducer was driven using a 100V<sub>pp</sub>, 630kHz, 5-cycle sine  
405 burst as determined by the peak frequency from the pulse-echo measurements  
406 (Section 2.3.1). Output data from PZFlex were further processed in MATLAB<sup>®</sup>  
407 R2014a (MathWorks, Natick, MA, USA). Spline and colour interpolation were used  
408 to smooth the output plots from the multi-parametric simulations.

409

### 410 *2.2 Isostatic pressure simulations*

411 SolidWorks<sup>®</sup> 2014 Premium (Dassault Systèmes, Vélizy-Villacoublay, France) was  
412 used to evaluate the transducer materials' ability to handle isostatic pressures using  
413 the in-built simulation package. Material properties were obtained from the standard  
414 software library and from the literature for PZ54 and epoxy [21], [22]. A static  
415 simulation was performed with a mesh node length of  $\leq 1.6$  mm (point of result  
416 convergence). An isostatic pressure was applied to the front face of the device and the  
417 case outer diameter was set as the fixed geometry. The isostatic surface pressure was  
418 increased incrementally in the range 0.35 – 6.90 MPa in 0.35 MPa (50 psi) steps. This  
419 pressure range was chosen as it corresponds to pressures at which petrochemical and  
420 liquefied petroleum gas pipelines operate [23]. The step size allowed visualisation of  
421 the stress and deformation close to the point of failure. The Von Mises stress  
422 distribution and deformation patterns were recorded.

423

## 424 **3 Results & Discussion**

425

### 426 **3.1 Design and fabrication**

427 Two issues were observed during prototype manufacture. First, concentrically  
428 aligning the glass and PZ54 ring was difficult when the epoxy was still in a fluid state.  
429 This was corrected by using polytetrafluoroethylene (PTFE) blocks to align the PZT  
430 ring in relation to glass using ink marking on the glass as a guide. PTFE is well  
431 known for its lack of adhesion. Second, air pockets were trapped between the glass

432 and the PZ54. This was avoided by placing the stack in a vacuum at 500 Pa for  
433 15 min prior to curing of the epoxy for 24 h.

434

### 435 **3.2 Acoustic Characterisation**

436 Electrical impedance measurements on the completed ultrasound transducers showed  
437 5 – 12 peaks in the spectra (**Figure 3**), attributed to extraneous resonance modes. In  
438 all impedance measurements, a drop in electrical reflection coefficient magnitude was  
439 observed in the frequency range 150 – 210 kHz. For Design 1:  $\delta = 0.133$  at 163 kHz;  
440 Design 2:  $\delta = 0.216$  at 152 kHz; Design 3:  $\delta = 0.086$  at 208 kHz; and Design 4:  
441  $\delta = 0.094$  at 210 kHz. Based on the widths of the PZ54 rings and the acoustic  
442 propagation properties,  $N_p = 2100 \text{ Hz m}^{-1}$ , it was concluded that these frequencies  
443 corresponded to the radial oscillation modes.

444 In all measurements, the second lowest value for  $\delta$  was observed at a higher  
445 frequency than the lowest value of  $\delta$ . For Design 1:  $\delta = 0.250$  at 367 kHz; Design 2:  
446  $\delta = 0.358$  at 475 kHz; Design 3:  $\delta = 0.412$  at 611 kHz; and Design 4:  $\delta = 0.331$  at  
447 634 kHz. Based on the thickness of the PZ54 ring and the acoustic propagation  
448 properties,  $N_T = 2000 \text{ Hz m}^{-1}$ , these frequencies were concluded to correspond to the  
449 thickness oscillation modes *i.e.*, the thickness mode resonance frequencies producing  
450 the required longitudinal ultrasound waves. Two to five peaks were observed between  
451 these two modes, identified as harmonics of the radial mode and other artefacts.

452 When comparing the electrical impedance measurements (**Figure 3**, black line) with  
453 the pulse-echo measurements (grey line), a distinct correlation was observed. Peaks  
454 were observed at both the radial and thickness mode frequencies, in addition to those  
455 relating to the intermediate modes. These indicate that either electrical impedance  
456 spectroscopy or acoustic pulse-echo measurements can be used to determine the  
457 behaviour of glass-windowed ultrasound transducers in under 5 min and that the  
458 facilities to carry out both tests are not needed.

459 **Table 2** shows the frequency characteristics obtained from the pulse-echo  
460 measurements using  $-3$  and  $-6$  dB cut-offs. The values of  $f_p$  are 110 kHz apart from  
461 Designs 1 ( $f_p = 350$  kHz) and 2 ( $f_p = 460$  kHz) even though nominally identical PZ54  
462 elements were used. As the structural differences between Design 3 and 4 are  
463 minimal, a smaller difference in  $f_p$  of 15 kHz was obtained.

464 Using a  $-3$  dB cut-off, BW was  $>65\%$  for all designs and using a  $-6$  dB cut-off BW  
465 was up to 97%.  $Q_m$  was in the range 0.59 – 0.81. In comparison, a commercially  
466 available single-element, air-backed, ultrasound transducer with a 500 kHz centre  
467 frequency has a  $-6$  dB bandwidth of 61.6% and  $Q_m$  of 0.61 [24].

468 The acoustic output power and pressure of the devices were also measured. **Figure 4**  
469 shows acoustic power output as a function of waveform generator voltage, measured  
470 using a radiation force balance. Whilst Designs 3 and 4 were significantly smaller,  
471 they were both able to produce over 4 W of acoustic power. In contrast, Designs 1 and  
472 2 were able to produce only approximately 2 W before the thickness mode expansion  
473 resulted in the PZT tensile stress reaching its limit. This issue may be solved by pre-  
474 stressing the elements [25]. A secondary limitation of this architecture was the build-  
475 up of heat. At 1 W output power, generated with a continuous wave at the peak  
476 frequency for each transducer for 60s the region of the case with the highest  
477 temperature increased to  $78 \pm 15^\circ\text{C}$  for Designs 1 and 2 and to  $88 \pm 10^\circ\text{C}$  for Designs 3  
478 and 4. The difference in temperature between the case and glass surface was within  
479 the  $\pm 2^\circ\text{C}$  error of the temperature gauge.

480 **Figure 5A** shows the pressure values calculated using **Eq. 4**. Design 1 produced the  
481 lowest acoustic pressure as a function of drive voltage and Design 2 produced the  
482 highest acoustic pressure. These results are in good agreement with the simulation  
483 data indicating that conversion from power to pressure is a valid operation. The only  
484 design for which correlation is poor is Design 1. This may be due to areas of adhesion  
485 failure between the glass disc and PZ54 ring resulting in a smaller than predicted  
486 cross-sectional area of maximum pressure closest to the transducer propagation face  
487 and hence increasing the derived acoustic pressure, based on Eq. 5.

488 Acoustic field scans were compared to simulations to validate the ability to predict the  
489 acoustic propagation pattern accurately (**Fig. 6**). The facial cross-sectional scans are  
490 able to differentiate the PZ54 ring and aluminium casing (**Fig. 6 F1 – 4**). In addition,  
491 concentric rings of higher and lower pressures with a peak directly in the centre are  
492 observed. This indicates that the glass may be oscillating like a diaphragm. In  
493 addition, the distance between these rings corresponds with the wavelength at the  
494 driving frequency.

495 Panels S1 – S4 (**Fig. 6**) show the simulated acoustic pressure profile for the different  
496 designs. It can be seen that completely different pressure fields are produced,  
497 depending on the design, with acoustic foci of different sizes at different locations.  
498 These variations may also be attributed partly to the different driving frequencies.  
499 Comparing the profiles to those measured experimentally, similar results were  
500 obtained. It is paramount to interpret the profile more than the position of colours as,  
501 due to unavoidable experimental misalignment ( $<1^\circ$ ), measurements were performed  
502 off plane, as a result altering the measured location of maxima. The experimental scan  
503 step size resulted in 6 – 9 samples within the smallest -6 dB profile. Reducing the step  
504 size may increase the acoustic profile in correspondence with the simulations.

505 **Figure 7** shows the transient response of each design at the acoustic focus when  
506 driven with a 5-cycle sine wave burst. Ringing was observed in all designs except  
507 Design 1 which exhibits damped properties, with a -20 dB ring-down period of only  
508 two cycles. Ring-down durations of 6 cycles for Design 2 and 12 cycles for Designs 3  
509 and 4 were observed. These results contrast with the expected measurements of BW  
510 and  $Q_m$  as, with large bandwidths and low  $Q_m$ , minimal ringing is expected. Here  
511 reduced ringing is observed, indicating damping. This may be due to the air-backing  
512 and increased isolation from the aluminium casing via 2.25 or 3.25 mm of epoxy. In  
513 Design 1, the glass is in direct contact with the aluminium case, which may increase  
514 damping and reduce ringing.

515 For all designs, subsequent signals were observed following ring-down. This is  
516 clearest in Design 1 (**Fig. 7**, red arrow). Increasing and decreasing the number of  
517 drive cycles did not change the number of cycles in the subsequent signals. Moving  
518 the hydrophone further from the transducer did not move the temporal location of the  
519 signals. This indicates that these signals were generated within the ultrasound  
520 transducers as a result of their architecture.

521 The Fourier spectra show a distinct peak at the drive frequency indicating acoustic  
522 fidelity. With increased ringing, increased harmonic activity was observed between  
523 1–2 MHz, *i.e.*, close to the 3<sup>rd</sup> harmonic.

524

### 525 **3.3 Acoustic Simulations**

526 **Figure 8** shows the simulated peak-to-peak axial acoustic pressure at the centre of  
527 each design as a function of several variables, based on Design 4. As the centre hole  
528 diameter is increased (**Figure 8A**) the furthest acoustic pressure maxima moves closer  
529 to the face of the transducer. For diameters between 7.5 and 11.5 mm, a new acoustic

530 focus starts to form at approximately 60mm from the transducer face. When the  
531 diameter is 14mm, an area of high acoustic pressure 50mm in length is observed,  
532 starting from the transducer surface. Varying the glass thickness (**Figure 8B**) results  
533 in the expected outcome: the maximum acoustic pressure is observed in the thickness  
534 range 2 – 4mm, corresponding approximately to  $\frac{1}{4}\lambda$ . This agrees with observation of  
535 maximum sensitivity from the experimental pulse-echo measurements. The highest  
536 acoustic pressure was observed with a glass radius of 14.5 mm, 0.5 mm smaller than  
537 the outer radius of the PZ54 ring (**Figure 8C**). Varying the driving frequency  
538 (**Figure 8D**) gives the predictable results that as the drive frequency reaches the  
539 resonance frequency of the device the acoustic pressure is maximized and an area of  
540 high acoustic pressure is formed furthest from the transducer surface. The simulations  
541 show the furthest and largest area of high acoustic pressure formed at approximately  
542 600kHz.

543 The agreement between the simulated and experimentally measured values indicates  
544 that this transducer architecture can be simulated and thus that simulations can be  
545 used to determine the optimal material dimensions (*i.e.*, glass thickness and mounting  
546 location, and PZ54 thickness, and inner and outer diameters) and drive frequency.  
547 All 480 simulations took 160 hours to solve, indicating an average simulation time of  
548 20 min. However this varies with transducer frequency. Reducing the drive frequency  
549 increases the element size and as a result reduces the required simulation time. Hence,  
550 at lower frequencies (~600kHz), a simulation took approximately 10 minutes whereas  
551 at higher frequencies (~1 MHz) a simulation took over 40 minutes. Subsequently,  
552 compiling, processing and plotting each dataset using an automated script took  
553 approximately 30 s.

554

### 555 **3.4 Stress and Deflection**

556

557 Isostatic pressure simulations (**Fig. 9**) show that the different designs result in  
558 different stress distribution profiles. Isostatic pressure applied to the front face of the  
559 device is shown with red arrows in **Figure 9:1a – 4a**. The case outer diameter was set  
560 as the fixed geometry, shown as green arrows in **Figure 9:1a – 4a**. The information  
561 gained from these simulations is important in applications where isostatic pressures  
562 up to 9.7 MPa (1400 psi) are applied, such as in the measurement of flow in high-  
563 pressure pipes [23].

564 Depending on the glass mounting location, the area of highest stress was found to  
565 vary (**Fig. 9:1b – 4b**). The largest stress distribution was observed with Design 2. The  
566 primary area of stress was in the glass in Designs 1 and 2, whereas the stress was  
567 distributed at the inner lower edge of the piezoelectric element in Designs 3 and 4. As  
568 expected, maximum deflection was observed at the centre of the transducers near the  
569 glass window. In Designs 1 and 2, deflection occurred primarily in the glass  
570 (**Fig. 9:1c–4c** red and yellow regions). In Designs 3 and 4, where the window is  
571 smaller, the area of maximum deflection was found to be in the piezoelectric element.  
572 The point of failure (PoF) was defined as the point at which the material stress  
573 surpasses the material tensile modulus of 48 MPa for fused quartz [26], and 45 MPa  
574 for PZT [27]. In the transducer architectures considered here, either the glass or PZ54  
575 reached the failure point first (**Fig. 10**) with the epoxy failing to reach the failure point  
576 because of its high elasticity. It should be noted that these simulations do not take into  
577 account the bonding strength between the epoxy, the PZT ring, and the metal casing,  
578 as this may be the first point of failure.

579 Design 1 was the weakest, showing glass failure at  $\sim 2.1$  MPa. This is due to the  
580 higher concentration of stress in a smaller area, and the larger amount of deflection.  
581 The PZT failed in Designs 3 and 4 at  $\sim 3.5$  MPa. However, this may not result in an  
582 operational failure as PZT is a ceramic and only a small portion of the PZT may be  
583 damaged allowing continued operation. Design 2 proved to be the strongest, with  
584 glass failure at  $\sim 4.8$  MPa. If the PoF is considered the point at which the glass fails,  
585 since this will certainly result in operational failure, then Designs 3 and 4 are  
586 considered the strongest, with failure observed at  $\sim 5.5$  MPa.  
587 All designs required  $< 50$   $\mu\text{m}$  of deformation (**Fig. 10B**) for failure to occur. If it was  
588 possible, redesigning the transducers to be more elastic or distributing the stress over  
589 a larger area would increase the pressure required to reach PoF.

## 591 **4 Conclusions**

592 A transducer architecture combining a central 10 – 20 mm diameter quartz glass  
593 window has been described, with four design variations operating at centre  
594 frequencies in the range  $350 < f_c < 630$  kHz constructed and simulated. The design  
595 variations were the dimensions of the piezoelectric ring, the diameter and thickness of  
596 the glass, and the location of attachment of the glass disc.

597 Based on the design variations, the architecture that has been described resulted in  
598 transducers with -6 dB bandwidths in the range 87 – 97%, acoustic output power of  
599 more than 1 W, and acoustic pressure of more than 1 MPa peak-to-peak.

600 The acoustic fields generated by the transducers were compared with simulations  
601 based on finite element analysis. The acoustic simulations were able to predict the  
602 behaviour of the fabricated devices. A total of 480 simulations with varying material  
603 dimensions indicated that design variations modify the emitted acoustic profile  
604 nonlinearly.

605 Isostatic pressure simulations indicated that specific design variations of this  
606 architecture could sustain isostatic pressures up to 4.8 MPa.

607

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611 Christian Michelsen Research AS.

612

613 **Tables**

Design	PZT			Glass		Case		
	ID	OD	TH	OD	TH	ID	OD	H
1	20	40	5	50	2	44.5	50	50
2	20	40	5	40	4	44.5	50	50
3	10	25	4	25	3	31.5	38	50
4	10	25	4	30	3	31.5	38	50

614 **Table 1:** Glass-windowed ultrasound transducer dimensions. All units are in mm.  
 615 (Key: ID – inner diameter, OD – outer diameter, TH – thickness, H – height)

616

Design	$f_p$ [kHz]	$f_c$ [kHz]		$f_l$ [kHz]		$f_u$ [kHz]		BW [kHz]		BW [%]		$Q_m$	
		-3 dB	-6 dB	-3 dB	-6 dB	-3 dB	-6 dB	-3 dB	-6 dB	-3 dB	-6 dB	-3 dB	-6 dB
1	350	436	465	294	240	577	689	283	449	65	97	0.81	1.28
2	460	419	430	258	232	580	627	322	395	77	92	0.70	0.86
3	615	550	547	366	308	734	785	368	477	67	87	0.60	0.78
4	630	549	539	362	297	735	780	373	483	68	90	0.59	0.77

**Table 2:** Acoustic properties of transducer designs calculated from pulse-echo measurements where  $f_p$  is the peak frequency,  $f_c$  is the centre frequency,  $f_l$  is the lower cut-off frequency,  $f_u$  is the upper cut-off frequency, BW is the bandwidth, and  $Q_m$  is the mechanical quality factor.



Variable	Lower value	Upper value	Step size	Number of steps
PZT hole diameter	2.0 mm	14.0 mm	0.1 mm	120
Glass thickness	1.0 mm	6.0 mm	415 $\mu\text{m}$	
Glass radius	12.6 mm	15.5 mm	242 $\mu\text{m}$	
Drive frequency	300 kHz	1.0 MHz	5.8 kHz	

**Table 3.** Variables, their ranges, and step sizes used to simulate the acoustic output pressure of the glass windowed ultrasound transducers.

## Figures

**Figure 1:** (A) Graphical representation of designs evaluated with cross-section illustrations depicting component location and geometry. (B) Schematic depicting labels for transducer geometry.

**Figure 2:** Acoustic power output from the four different designs as a function of peak-to-peak waveform generator voltage amplitude measured using an acoustic radiation force balance. The tapering off at high acoustic power levels indicates the tensile stress in the PZT is reaching its tensile strength.

**Figure 3:** Electrical impedance reflection coefficient (left axis, black line) and normalised frequency sensitivity (right axis, grey line) of devices. A lower electrical reflection coefficient is considered optimal whilst a large magnitude frequency sensitivity indicates optimal working frequency. A direct correlation between electrical impedance reflection coefficient and frequency sensitivity can be seen.

**Figure 4:** Acoustic power output from the four different designs as a function of peak-to-peak waveform generator voltage amplitude measured using an acoustic radiation force balance. The tapering off at high acoustic power levels indicates the tensile stress in the PZT is reaching its tensile strength.

**Figure 5:** Measured and simulated acoustic pressures in focal zone of the four designs as a function of peak-to-peak waveform generator voltage amplitude. A direct correlation can be seen between the experimental measurements and simulations.

**Figure 6:** Field scans and corresponding simulations of a 5-cycle pulse from the four different transducers designs indicating the acoustic pressure profile. F1 – F4 show the measured profile approximately 1 mm from the face of the transducer ( $x$ - $y$ ). S1 – S4 show the simulated data in the axial direction ( $z$ - $y$ ), and M1 – M4 show the equivalent measured data. All frames are identical scale, where the scale bar represents 10 mm. Measurements were performed using a 500  $\mu\text{m}$  step size, where as simulation were performed using a  $1/50^\circ$  resolution.

**Figure 7:** Transient response and corresponding frequency spectra of the four transducer designs. The distance ( $d$ ) between hydrophone and transducer is shown in the respective panel. Red arrow and indicate region show additional acoustic activity generated from the ultrasound transducer. Design 1 shows minimal ringing whereas Designs 2 – 4 show increased ringing, which corresponds with higher harmonic content.

**Figure 8:** Multi-parametric simulations comparing the axial peak-peak acoustic pressure as a function of (A) central hole diameter, (B) glass thickness, (C) glass radius, and (D) driving frequency. Acoustic profiles were simulated for Design 4, using a 5-cycle sine-wave burst as the electrical input. A complex interaction can be seen for changes in construction geometry.

**Figure 9:** Isostatic stress simulation setup and results. (a) Mesh, (b) stress, and (c) deflection distributions are shown in the four transducer designs when an isostatic load is applied to the front face. Maximum deflection is observed in the centre of the device. Peak stress is observed in the centre of the glass for Designs 1 and 2, and in the PZT for Designs 3 and 4.

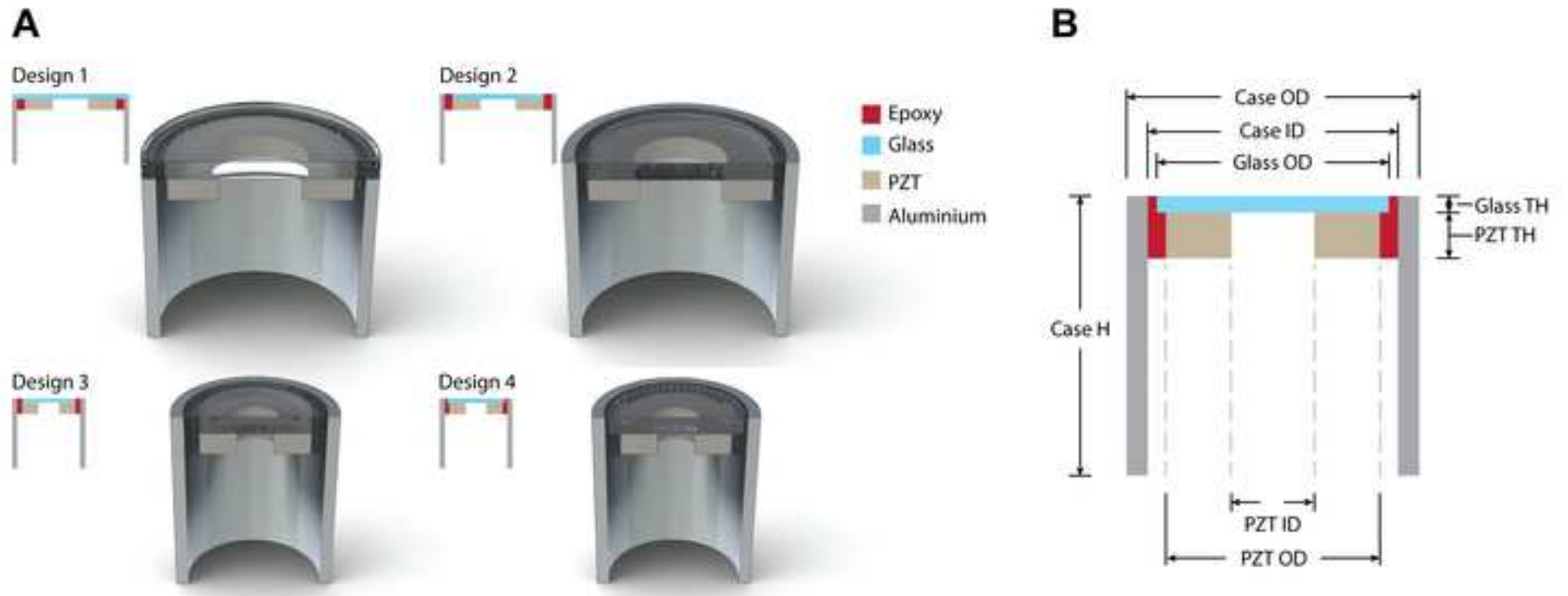
**Figure 10:** Simulation results indicating peak Von Mises stress and deformation in the four designs as a function of isostatic loading on the front face. Gray and black dots indicate points of failure and which material surpasses its tensile modulus first.

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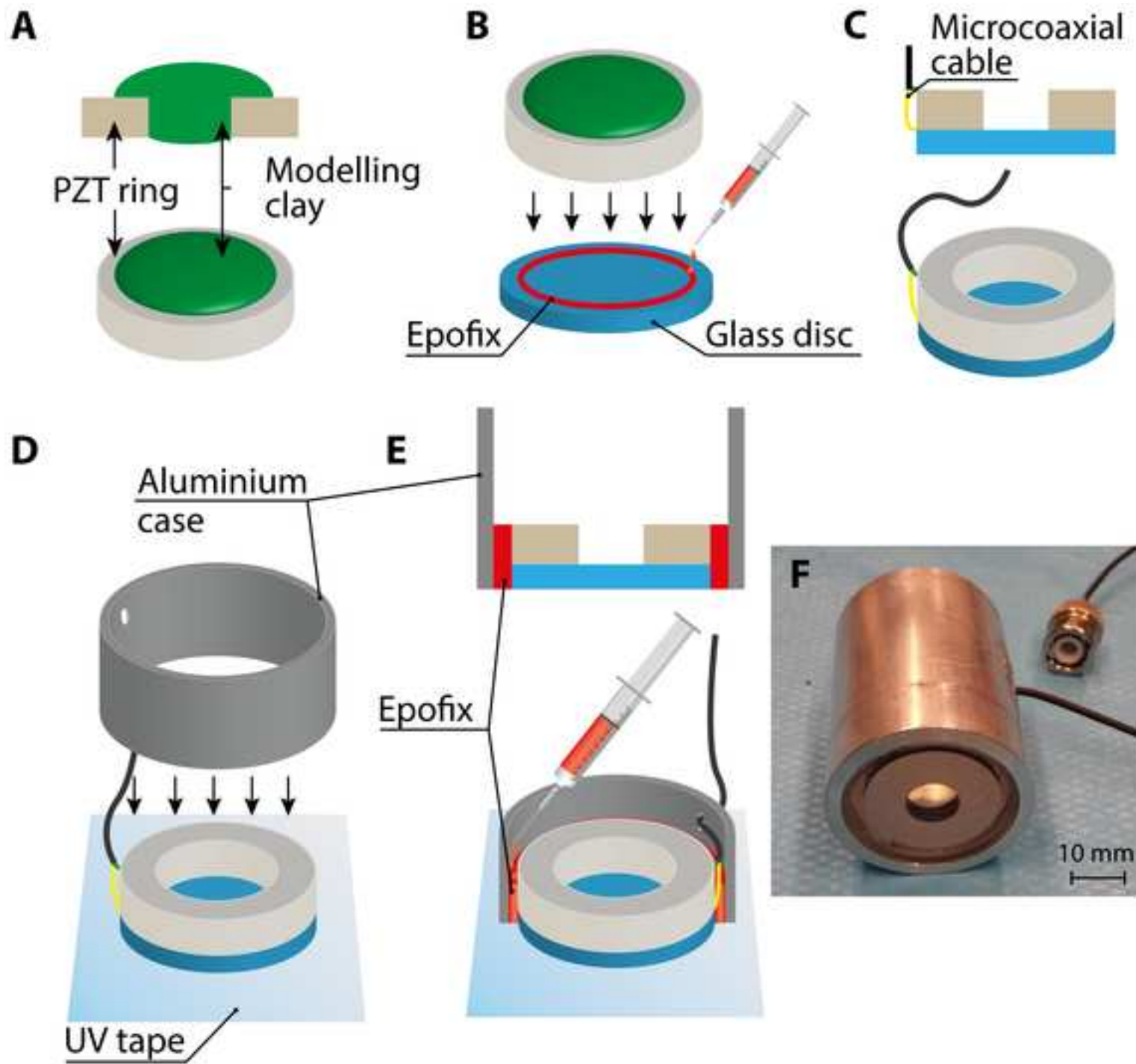
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Figure\_1  
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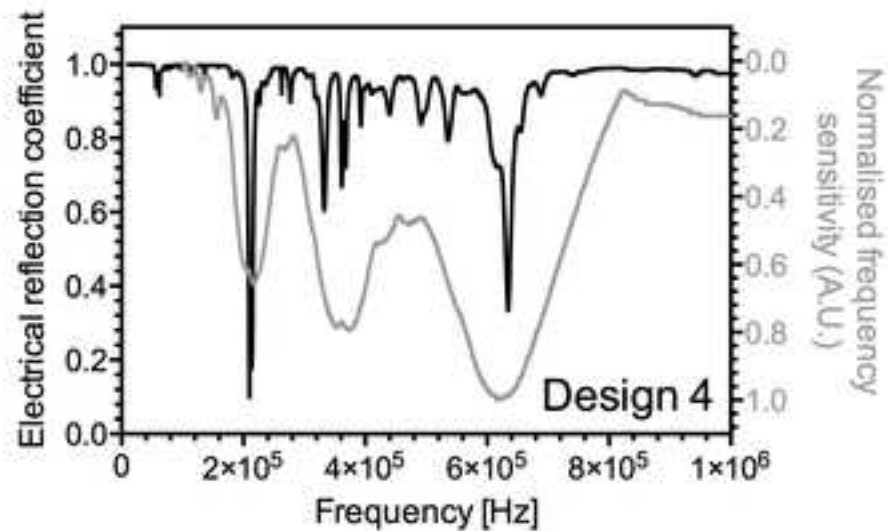
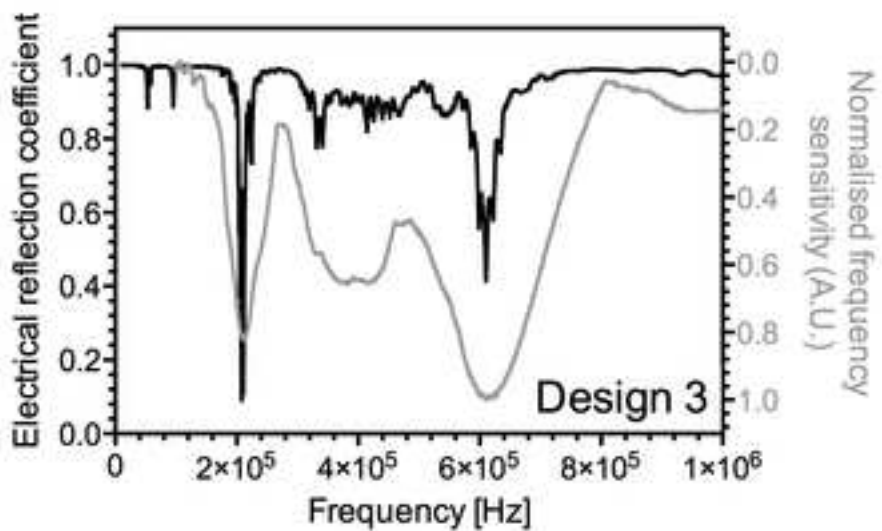
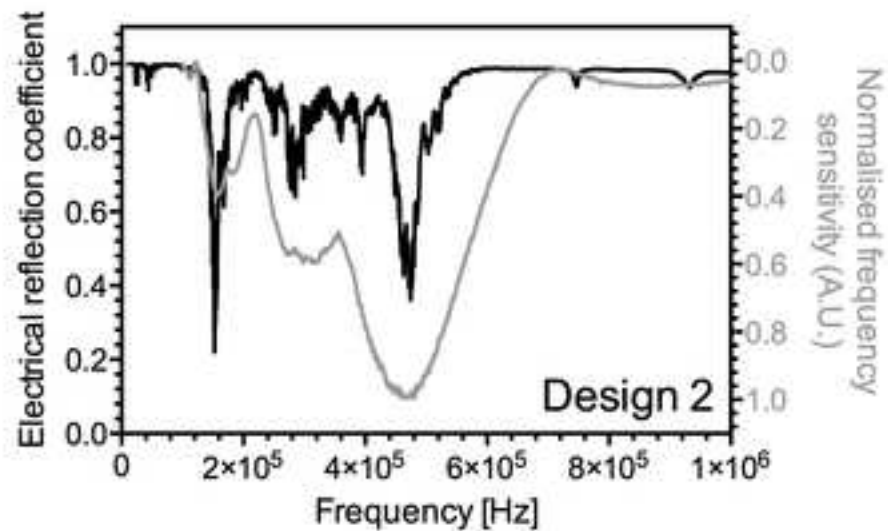
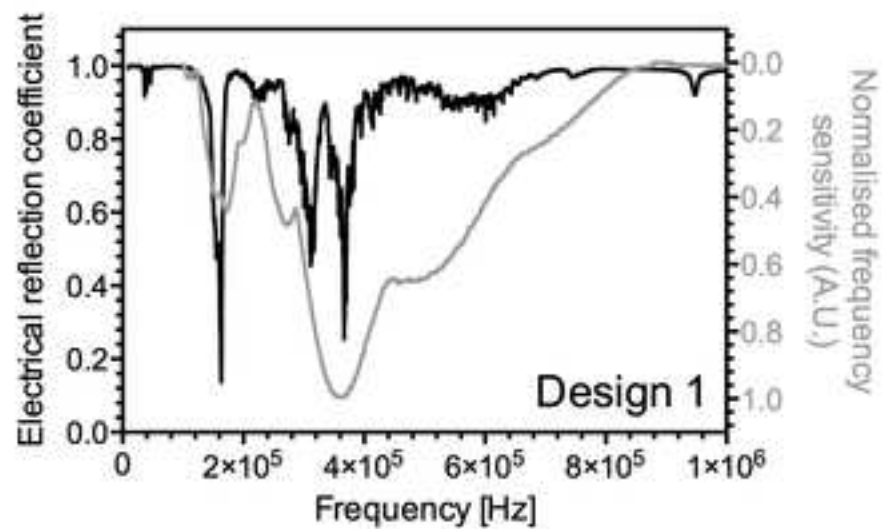


Figure\_2  
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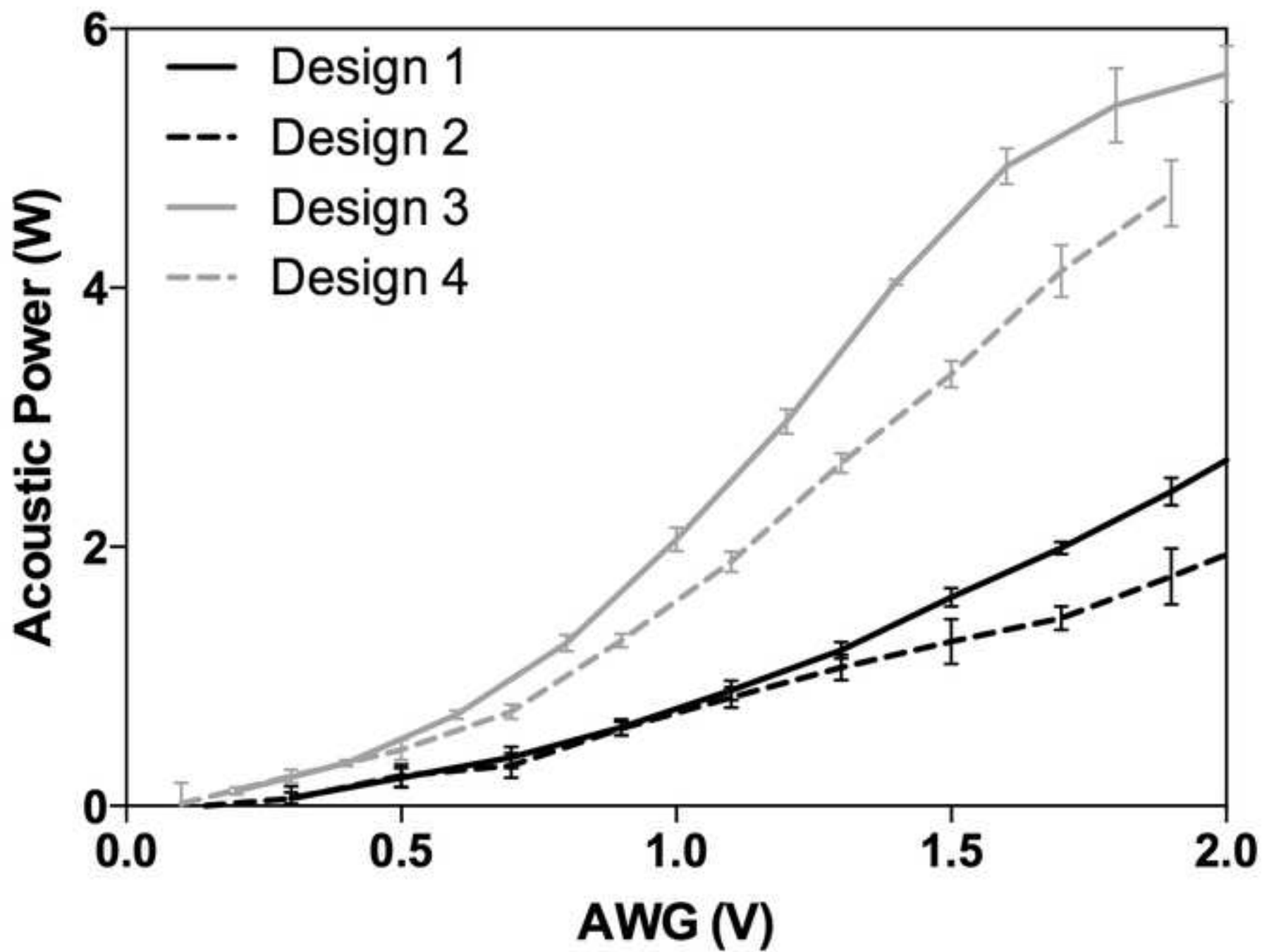
Figure\_3

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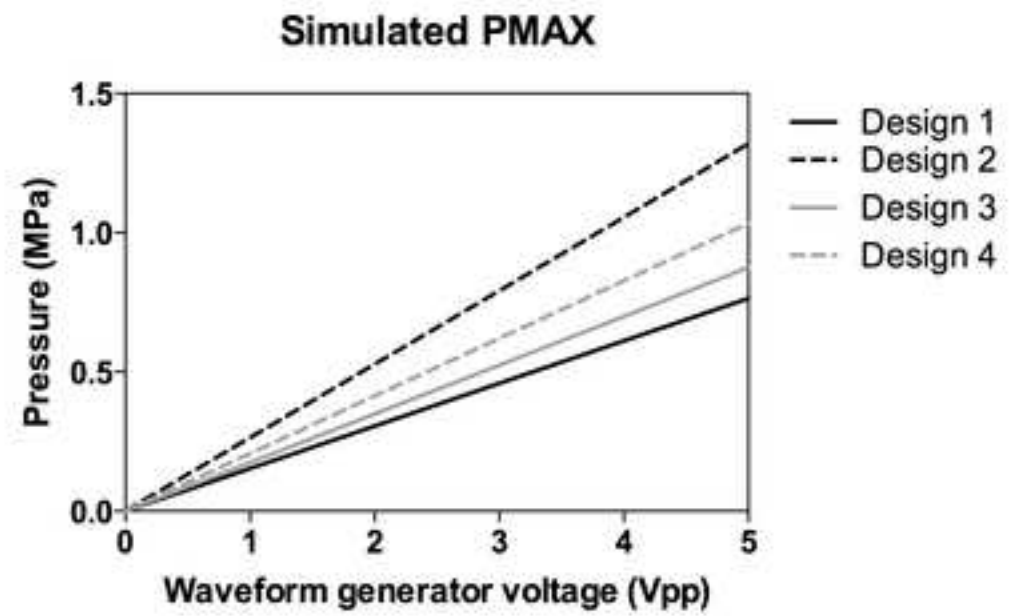
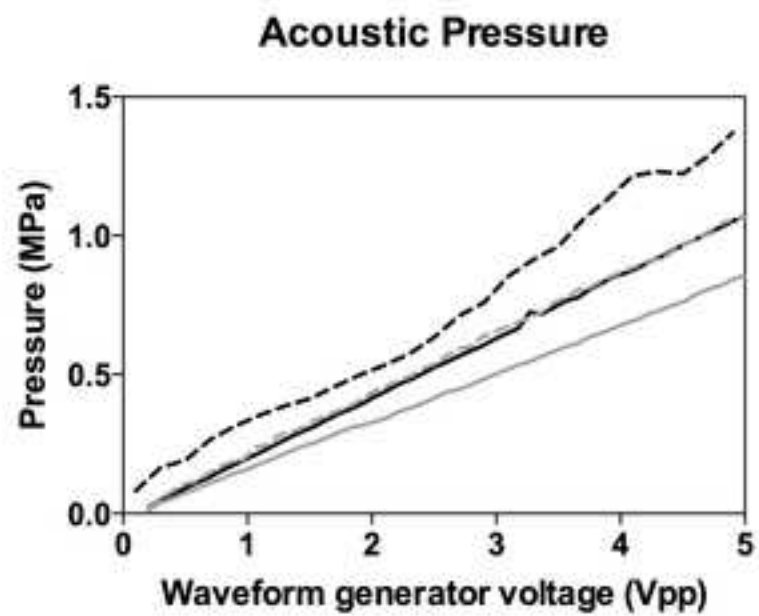


Figure\_4  
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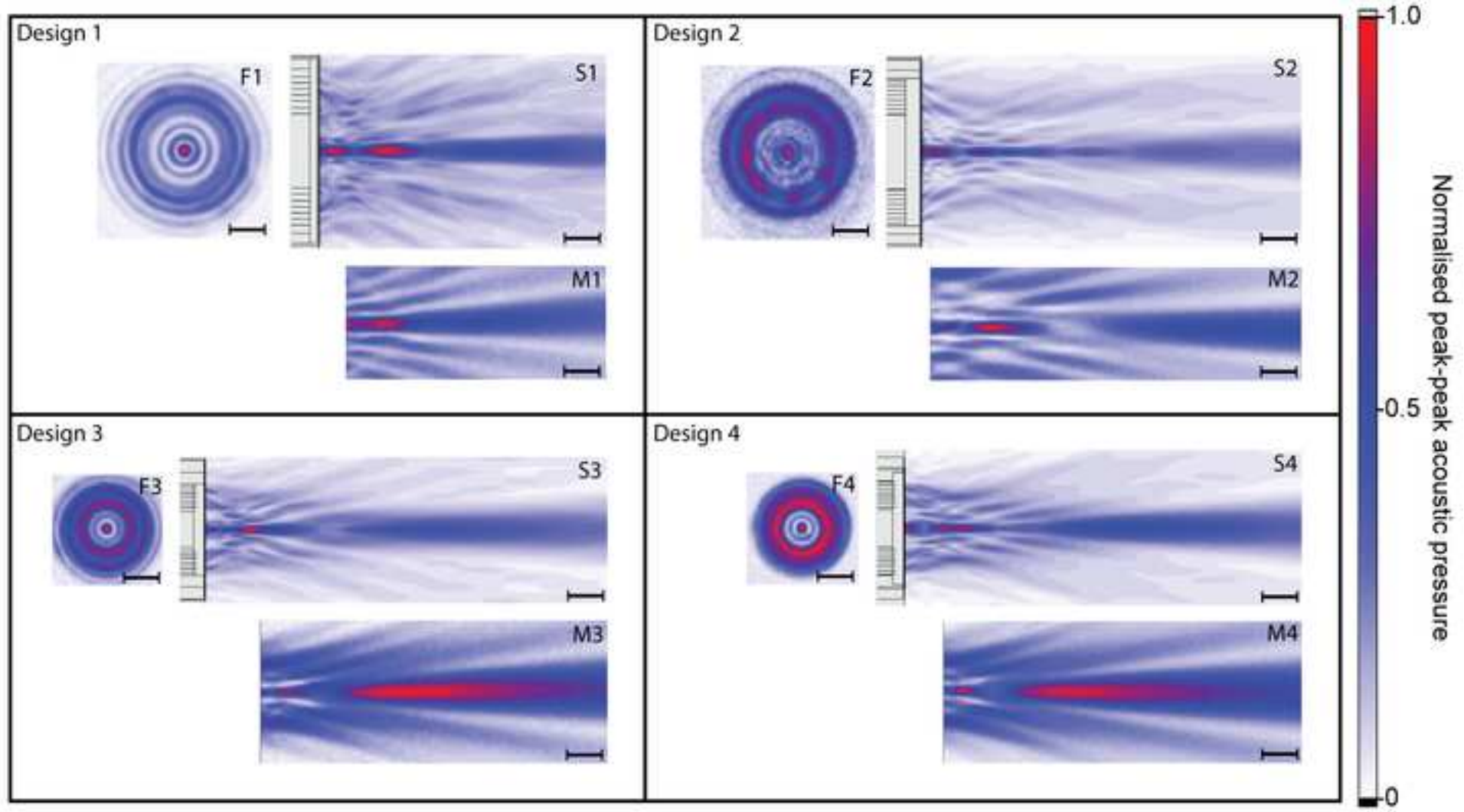


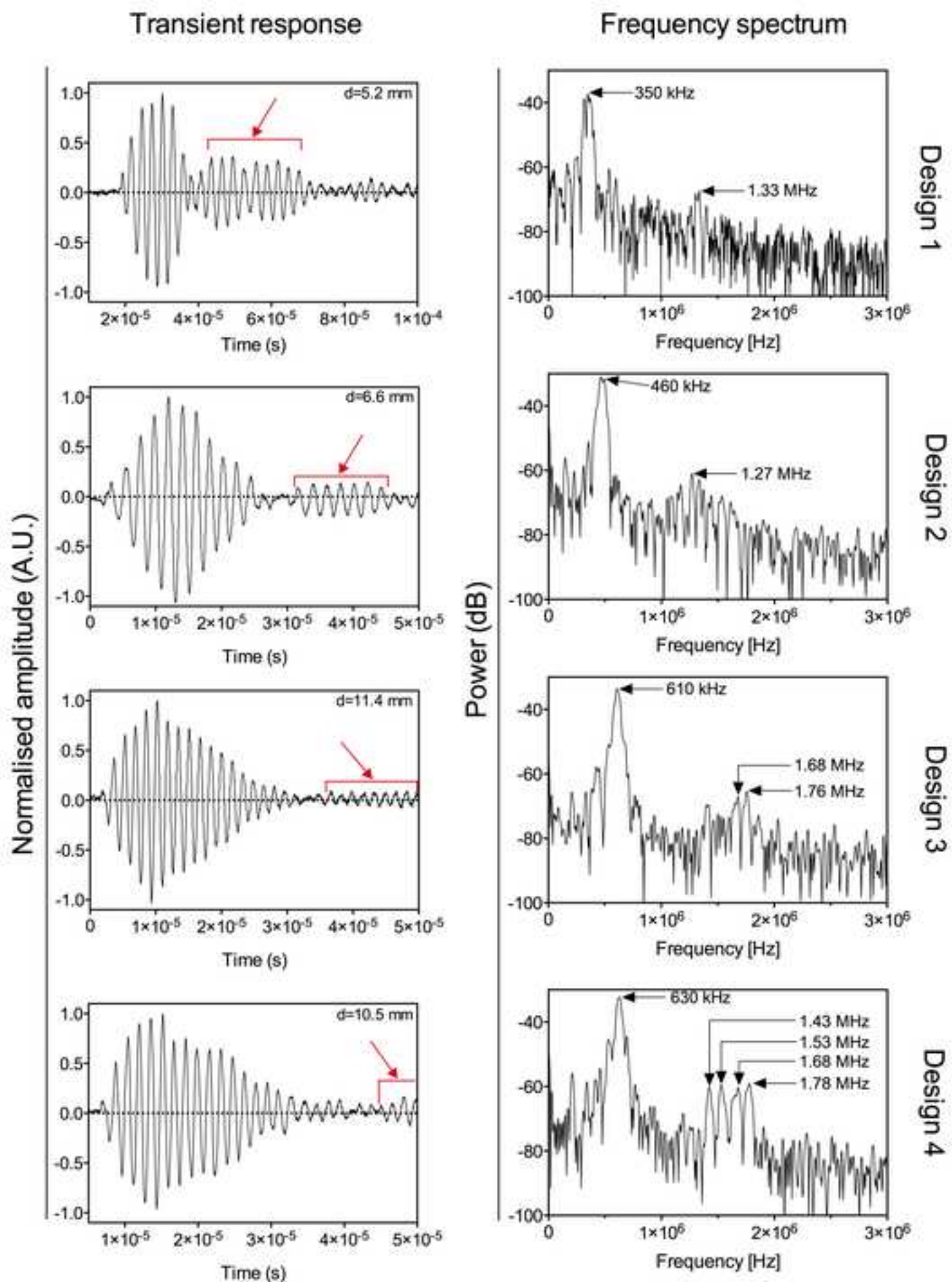
Figure\_5

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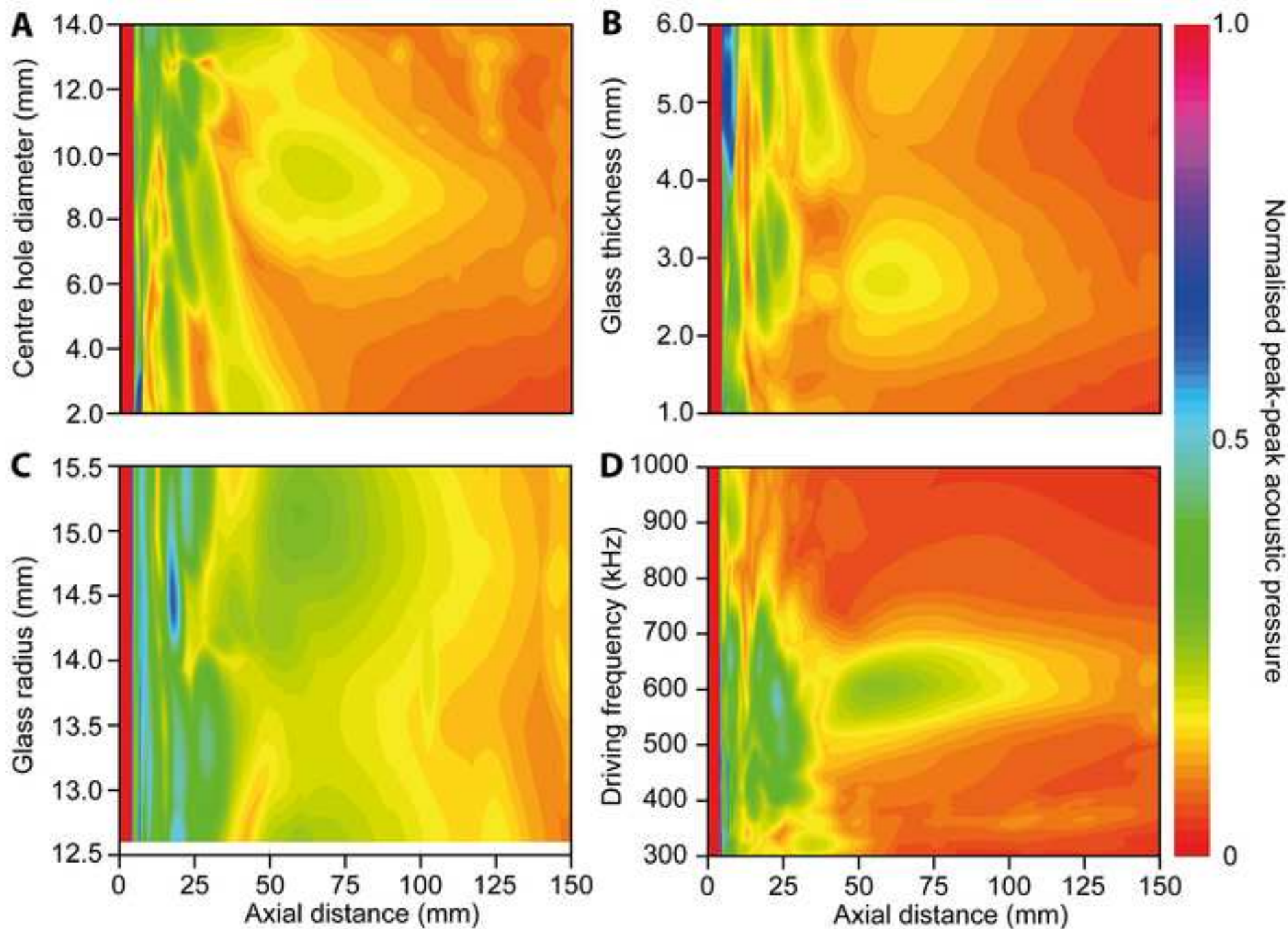


Figure\_6  
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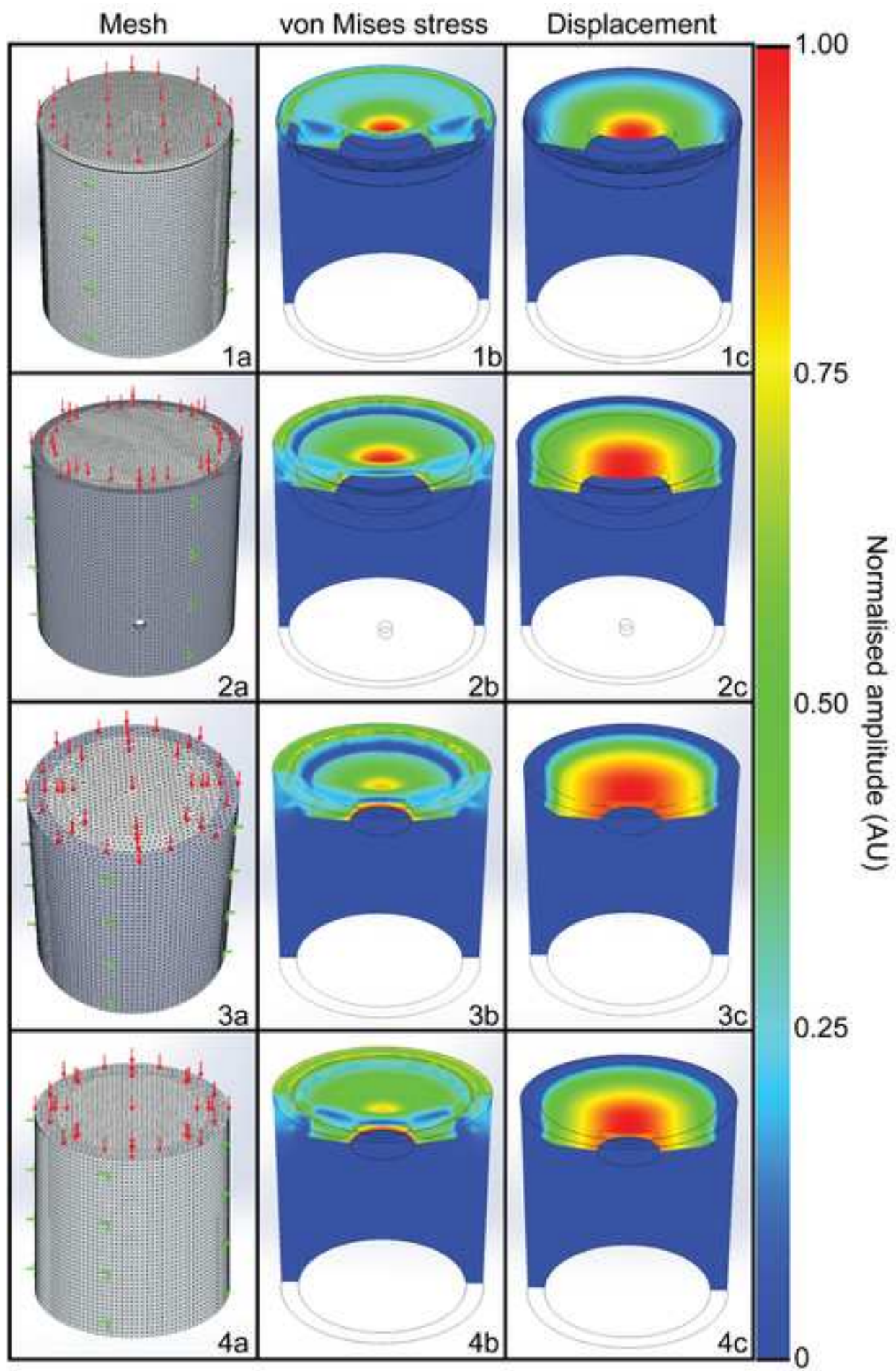


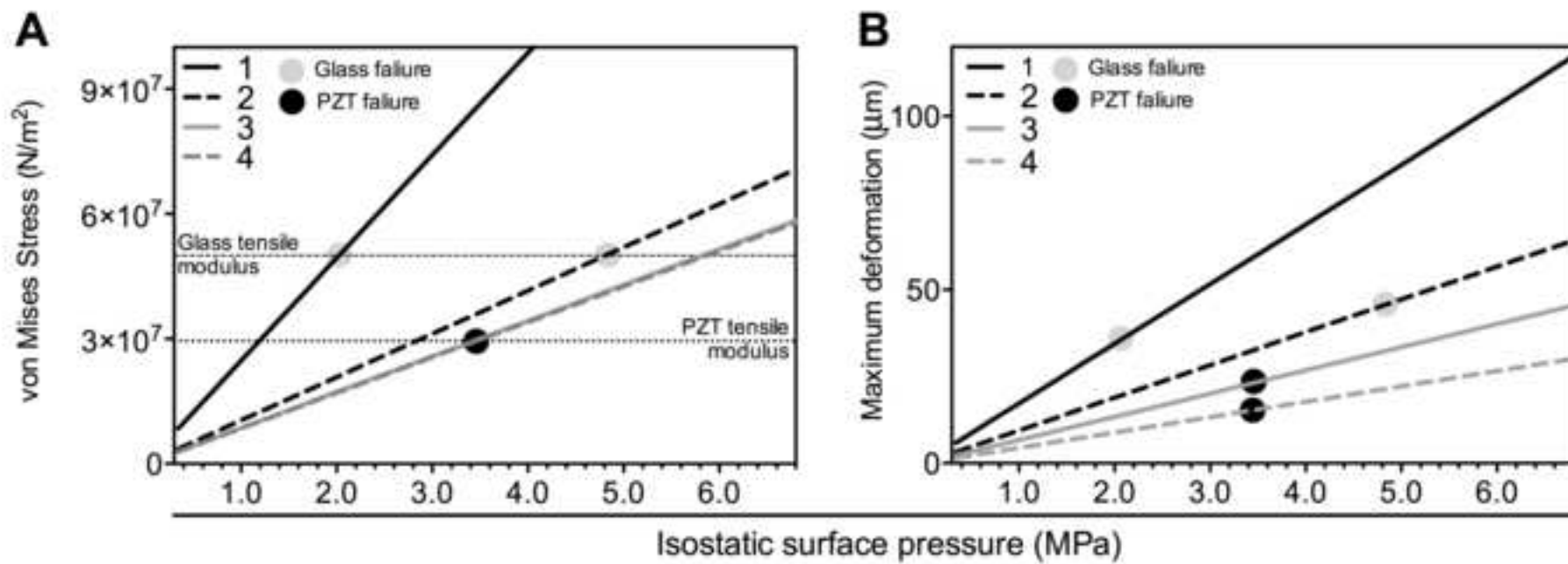
Figure\_8  
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Figure\_9

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## Highlights

- An ultrasound transducer with a glass optical window constructed and simulated.
- Devices produced bandwidths  $>87\%$ , powers  $>1$  W, and pressures  $> 1$  MPa.
- Finite element analysis was able to predict the acoustic pressure and beam profile.