CRYOULTRASONIC NDE

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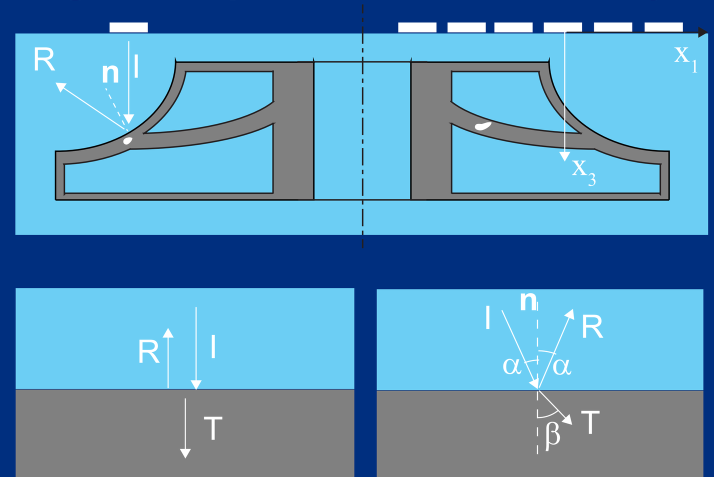
INTRODUCTION

The inspection of complex-shaped parts, which may contain multiple internal vanes and present highly curved surfaces, poses a major challenge to conventional NDE techniques. Cryoultrasonic NDE uses the remarkable properties of ice to transform a complex-shaped part into a simple-shaped solid which can then be inspected by combining ultrasonic array measurements with advanced imaging methods.

ULTRASONIC TRANSMISSION & REFLECTION



Normal incidence transmitted and reflected wave intensities

$$\frac{I_T}{I} = \frac{4B}{(B+1)^2} \qquad \frac{I_R}{I} = \frac{(B-1)^2}{(B+1)^2}$$

B ratio between acoustic impedances, *Z*, of two media in contact

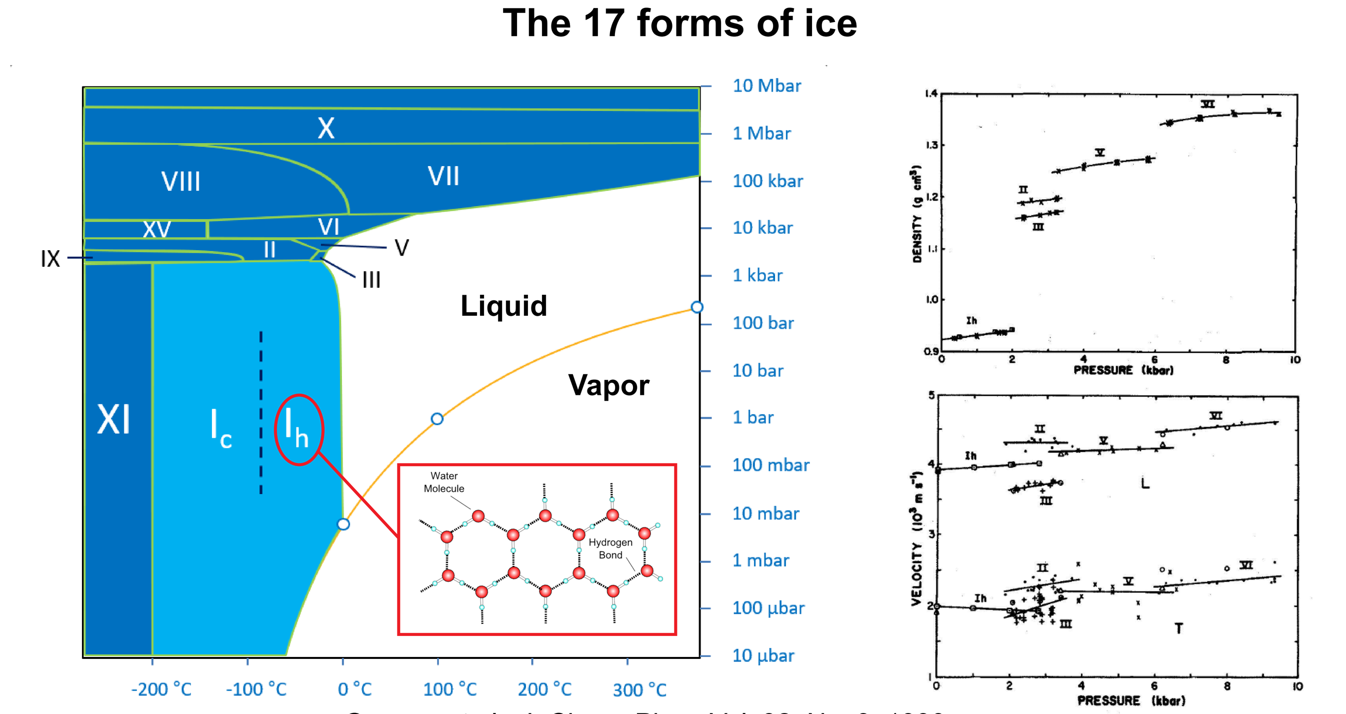
$$Z = \rho\, c$$

ρ mass density, *c* ultrasonic velocity

Total reflection occurs when a wave is incident on a fast medium, c_f, from a slow medium, c_f, at an angle equal or greater than $\alpha_{cr}=\arcsin(c_s/c_f)$. Therefore, conventional immersion testing is not suitable to penetrate multiple water-metal interfaces. Ice provides a superior coupling medium which increases transmission and boosts α_{cr}

			Water Immersion			Ice (Ih) encapsulation		
Material	c [m s^{-1}]	[kg m^{-3}]	I_T/I	I_R/I	α_{cr} [deg]	I_T/I	I_R/I	α_{cr} [deg]
Plexiglass	2730	1180	0.86	0.14	32.8	1.00	0.00	N/A
Aluminum	6320	2700	0.29	0.71	13.5	0.57	0.43	37.5
CMC	6850	2800	0.27	0.73	12.5	0.53	0.47	34.2
Ti-6Al-4V	6170	4430	0.19	0.81	13.9	0.41	0.59	38.6
Steel	5890	7800	0.12	0.88	14.6	0.27	0.73	40.8
Inconel	5720	8250	0.12	0.88	15.0	0.26	0.74	42.3
Copper	4750	8930	0.13	0.87	18.2	0.28	0.72	54.1

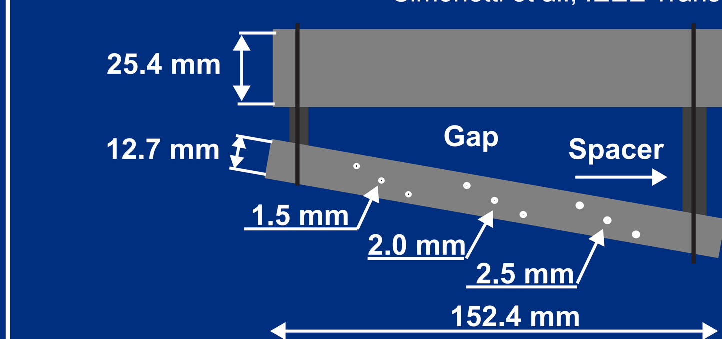
The 17 forms of ice

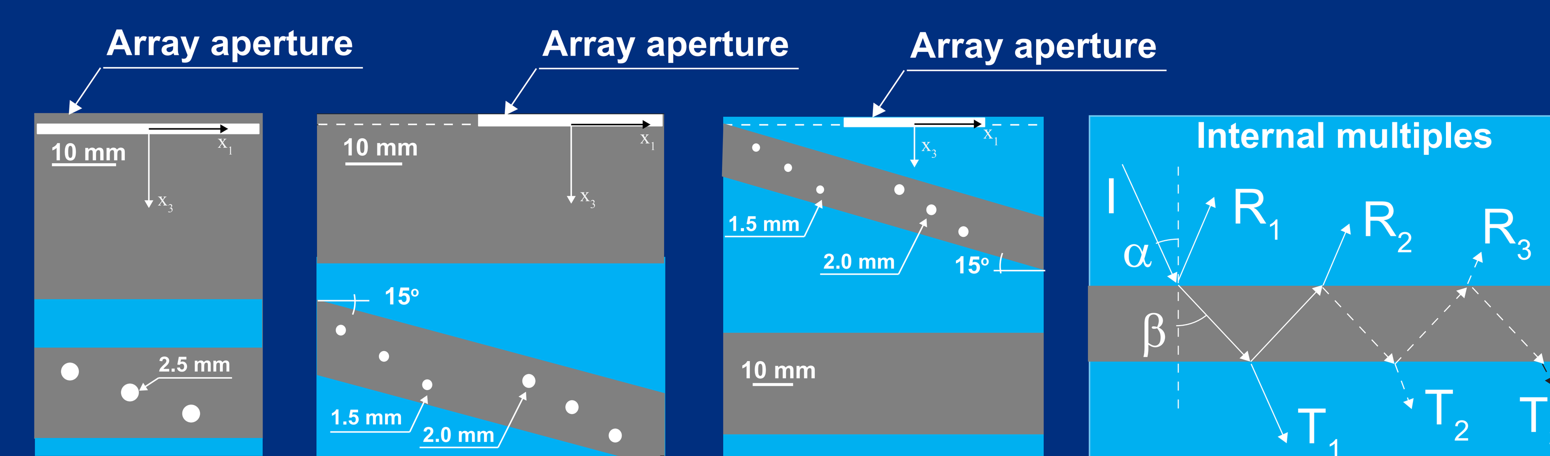


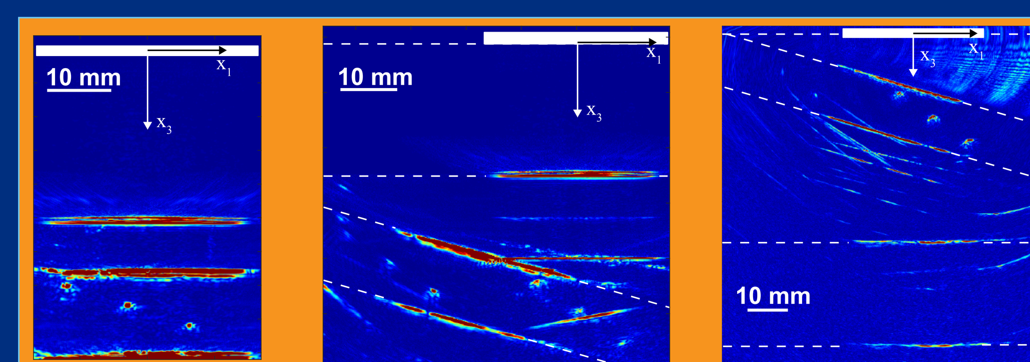
Gagnon et al., J. Chem. Phys. Vol. **92**, No. 3, 1990

FIRST CRYOULTRASONIC EXPERIMENTS

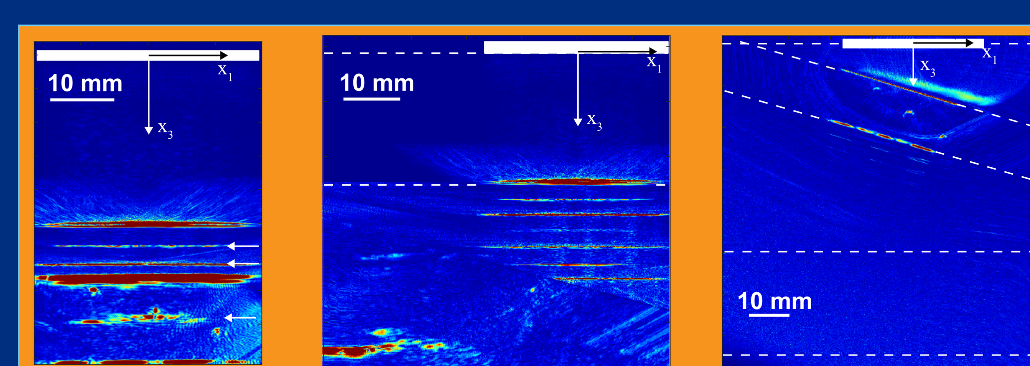
Simonetti et al., IEEE Trans. Ultrason. Ferroelect. Freq. Cont., Vol. **65**, No. 4, 2018







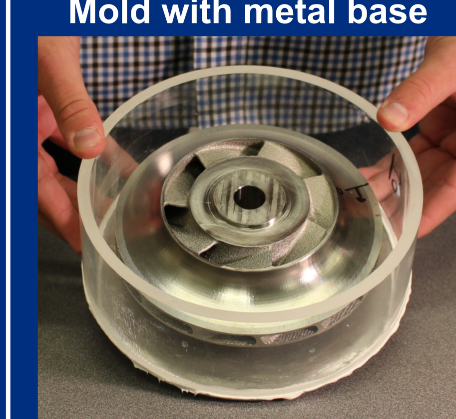
Ultras. images in ice (10 MHz)
- Multiple ice-aluminum interfaces are reconstructed
- All defects detected
- Field of view extends beyond array aperture
- Artifacts appear due to internal multiples



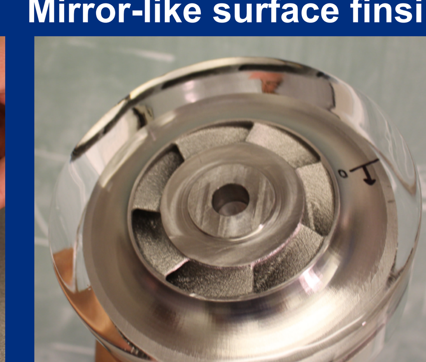
Ultras. images in liquid water (10 MHz)
- Bottom plate not visible when plates are slanted
- Stronger artifacts due to internal multiples
- Higher image noise
- Low defect sensitivity

UNIDIRECTIONAL FREEZING METHOD

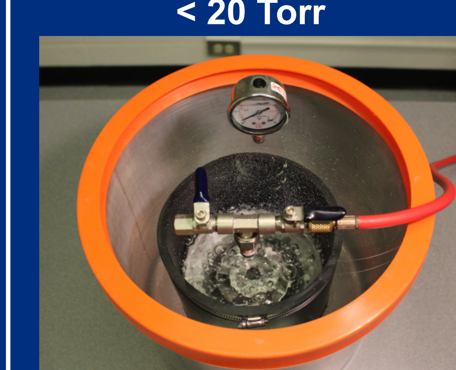
Mold with metal base

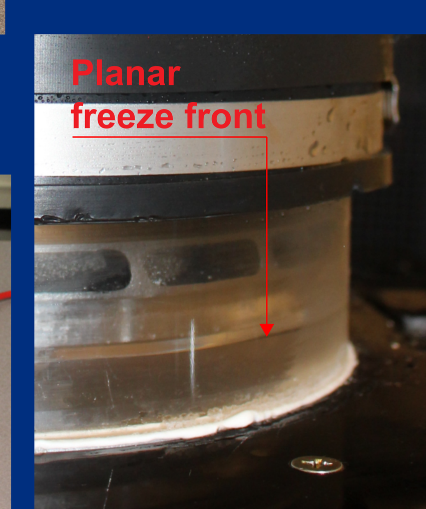


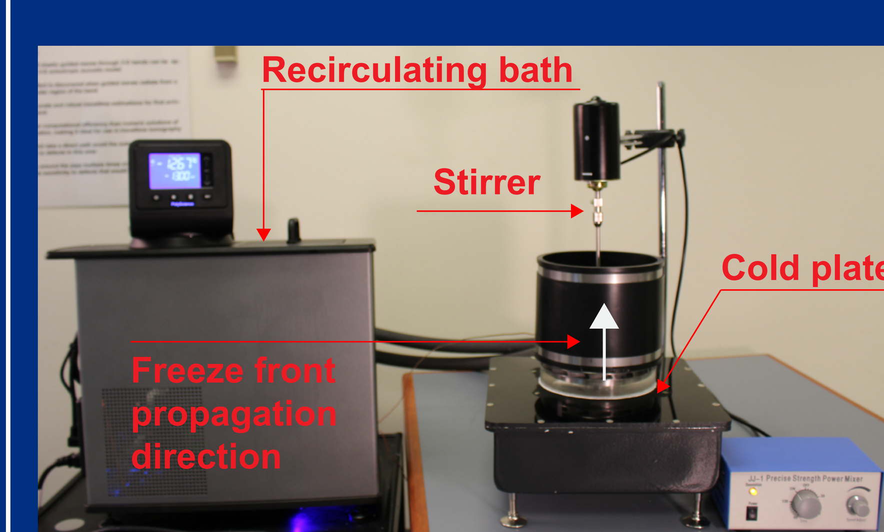
Mirror-like surface finsih



Vacuum degassing at < 20 Torr







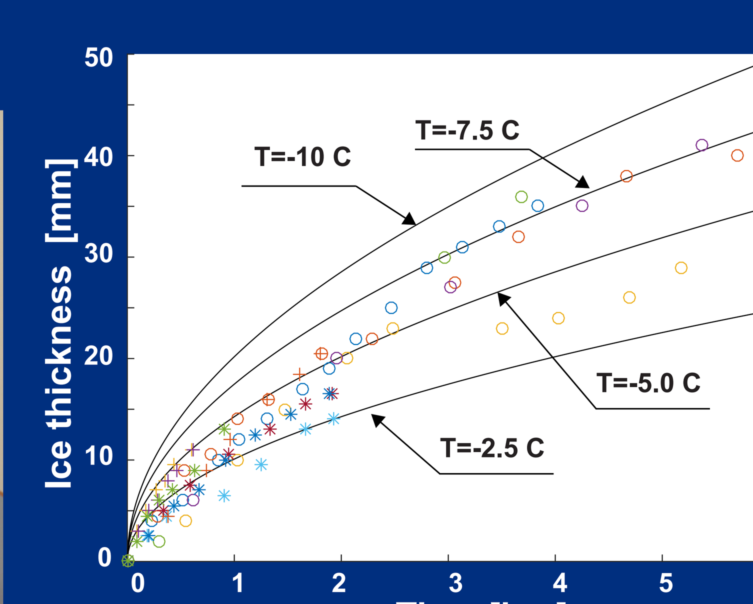
Freeze front propagation model at constant cold plate temperature

$$h = \sqrt{atT}$$

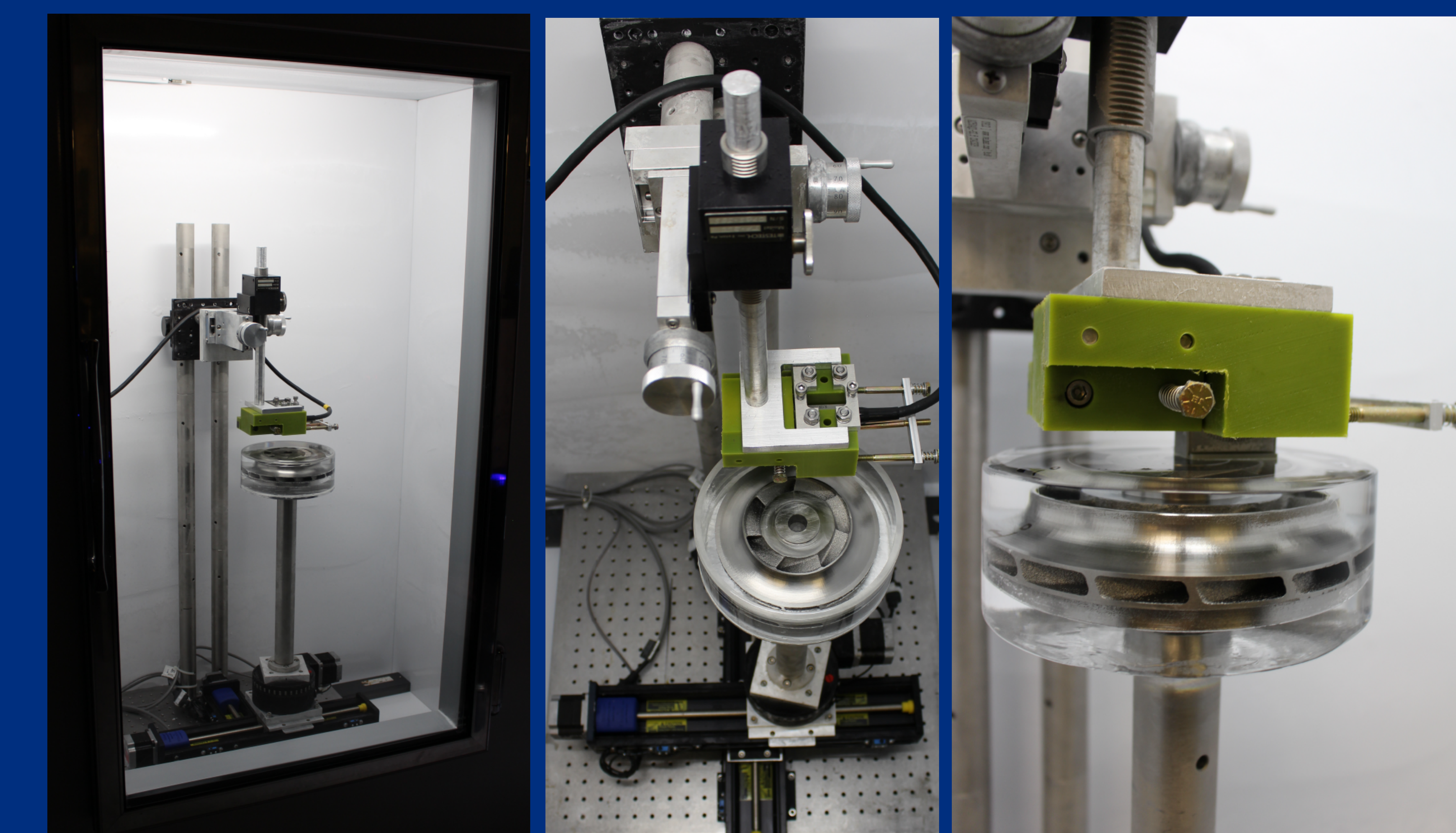
h ice thickness [m]
t time [sec]
T cold plate temperature [C]
a material constant

$$a = \frac{2k}{\lambda\rho}$$

k thermal conductivity W/mC
λ latent heat [J/kg]
ρ mass density [kg/m³]

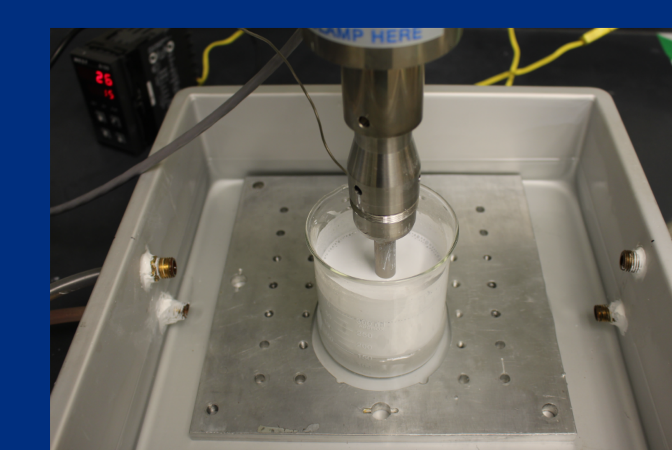


PROTOTYPE CRYO-SCANNER



- The scanner is enclosed in a test cell that maintains temperature at -10 C
- Two linear stages allow x-y scans with 5 μm resolution
- One rotary stage enables angular scans with 0.025 deg resolution.
- Fixture with 3-axis spring loading ensures ideal coupling of array to ice surface
- AOS 256 parallel channel array controller drives the array probe
- Data acquired at 14 bits, 100 MHz sampling rate through USB 3 (160 MB/s) +LAN@ 1Gb
- 128-element full matrix capture (FMC) + writing to disk in under 10 sec
- Full volume coverage of the specimen in the photograph is obtained by recording 360 FMC datasets in under one hour. A total of 5.9 M waveforms is acquired resulting in 30 Gb of ultrasonic data

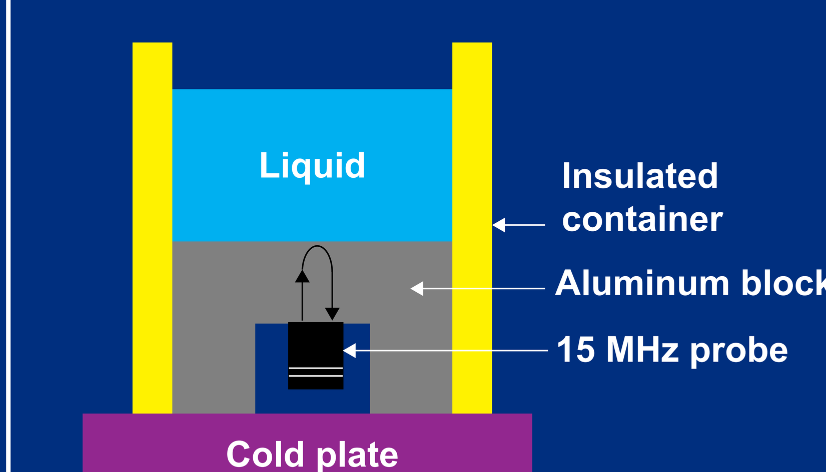
ICE NANOCOMPOSITES

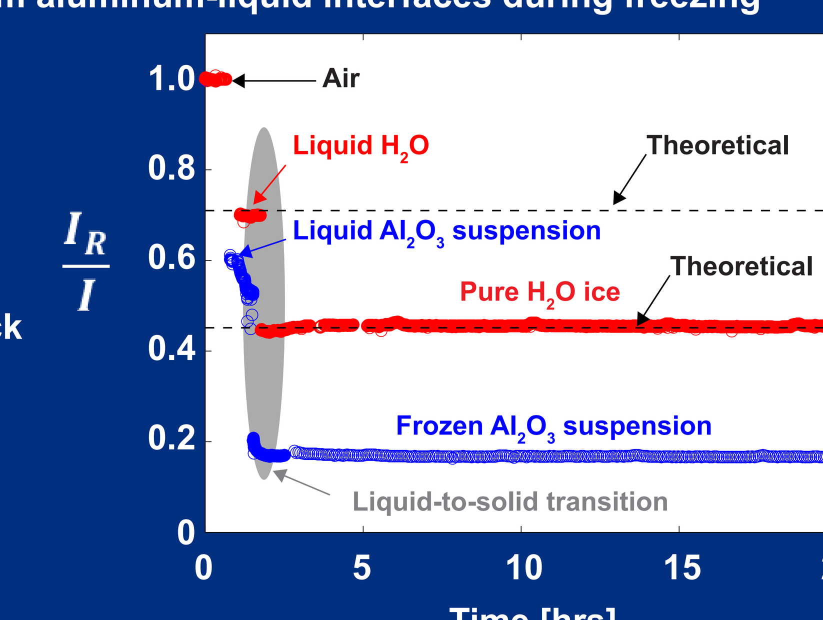


Freeze aqueous suspensions of nanoparticles to increase the impedance of ice

- Used alumina (Al_2O_3) nanoparticles
- Sonication to mix powder and water
- Stabilization achieved by adding HCl
- Suspension with 60% WT alumina content exhibits very low viscosity, like liquid paint

Monitoring the ultrasonic reflection from aluminum-liquid interfaces during freezing





CONCLUSIONS

- Ice is an ideal solid ultrasonic couplant owing to its high velocity, low attenuation, and excellent adhesion properties to metals
- Ice nanocomposites show significant potential to further increase velocity and mass density while reducing freezing time
- Unidirectional freezing technique ready to encase parts in crystal clear ice blocks free from bubbles and cracks
- First cryo-scanner integrated with ultrasonic array controller for rapid inspection of real components
- Ongoing work on advanced imaging methods to account for internal multiples and develop first application of transmission tomography for metal parts