# CUDARFI: CUDA-Accelerated ARFI Beamforming

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## Background

Acoustic Radiation Force Impulse (ARFI) imaging uses focused ultrasound to induce localized tissue displacement. By tracking the resulting shear waves, ARFI provides quantitative information about tissue stiffness, enabling non-invasive assessment of conditions like liver fibrosis or breast lesions.

## Algorithm & Optimization

**1. Hilbert Transform (FFTW)**
RF signals are real-valued; converting them to complex analytic signals enables envelope detection and phase tracking. The analytic signal is: $s_a(t) = s(t) + jH\{s(t)\}$, computed via FFT by zeroing negative frequencies and applying IFFT.

**2. Delay-and-Sum Beamforming (CUDA)**
For each output pixel at position $(x, z)$, signals from all $N$ transducer elements are coherently summed after applying appropriate time delays:

$$I(x,z) = \sum_{i=1}^{N} S_i \left( \frac{\sqrt{(x-x_i)^2 + (z-z_i)^2}}{c} + t_0 \right)$$

Here, $(x_i, z_i)$ is the position of element $i$, $c$ is sound speed, and $t_0$ is the initial time offset. Linear interpolation provides sub-sample precision.

**3. Kasai Autocorrelation (Python)**
Tissue displacement $d$ is estimated from the phase shift between consecutive beamformed frames $I_n$ and $I_{n-1}$:

$$d = \frac{c}{4\pi f_0} \angle (I_n \cdot I_{n-1}^*)$$

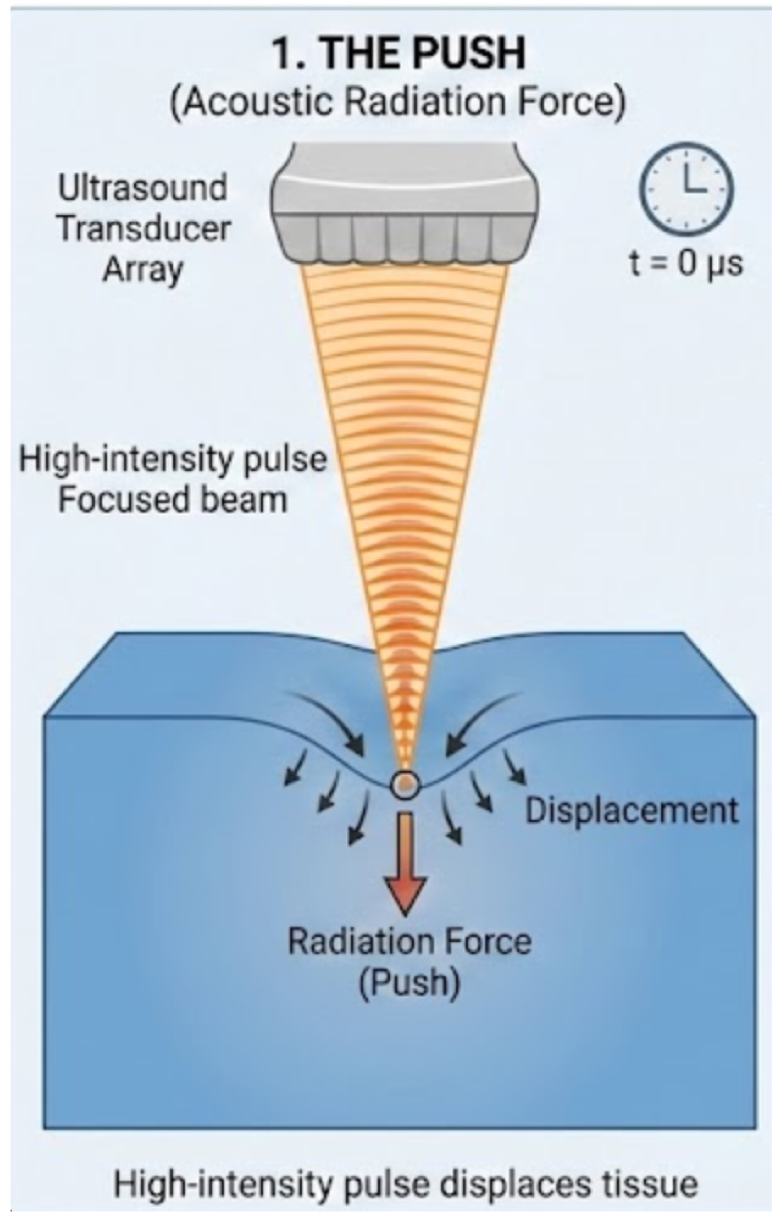
where $f_0$ is the center frequency. A spatial averaging filter smooths the noisy phase estimates.

**CUDA Optimizations:**

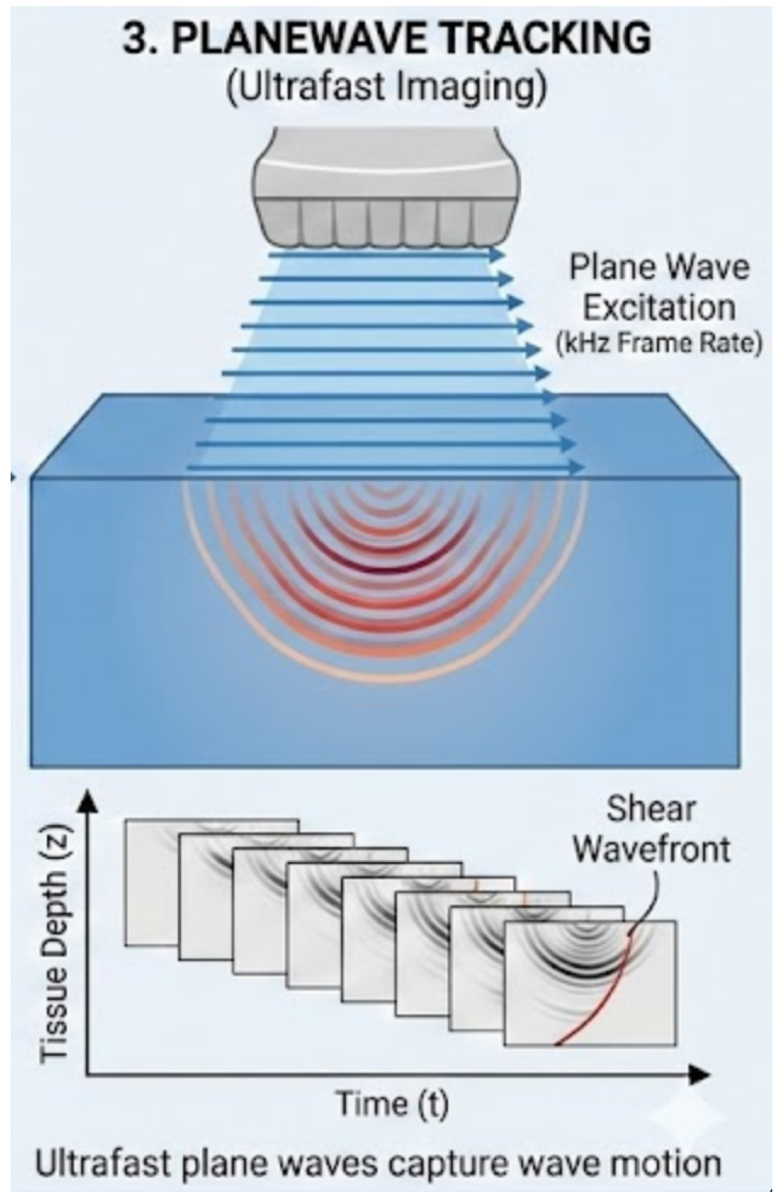
- **Texture Cache**: `__ldg()` for read-only cache.
- **Constant Memory**: Probe geometry broadcast.
- **Fast Math**: (`__fsqrt_rn`, `__fmaf_rn`).
- **Launch Bounds**: `__launch_bounds__(256)`.
- **Precomputed Inverses**: Avoid division by precalculating $1/c$.

## Experimental Setup

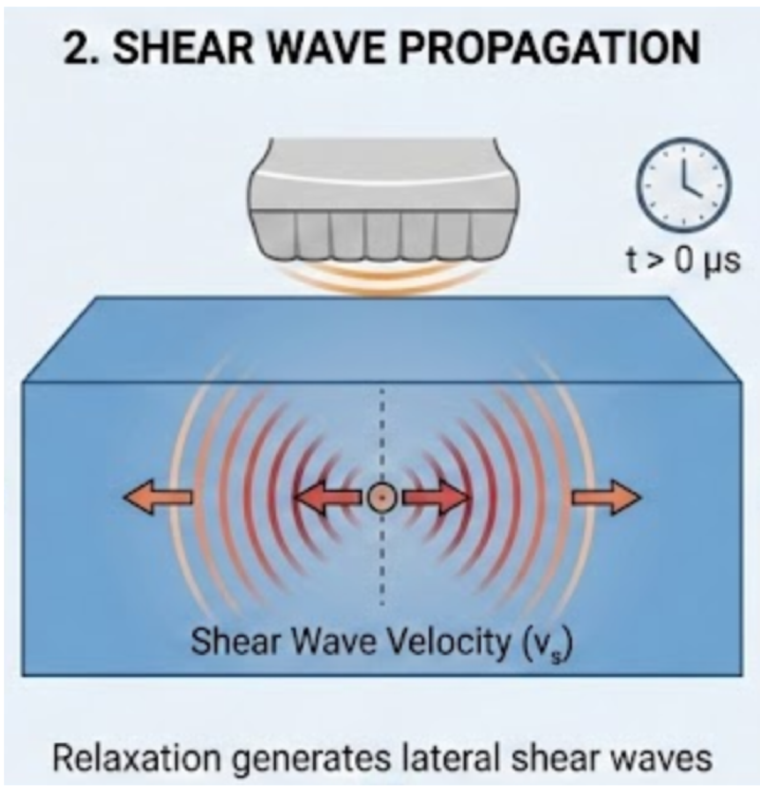
The setup utilizes a CIRS phantom imaged with a Verasonics Vantage system.




Schema 1: Geometry



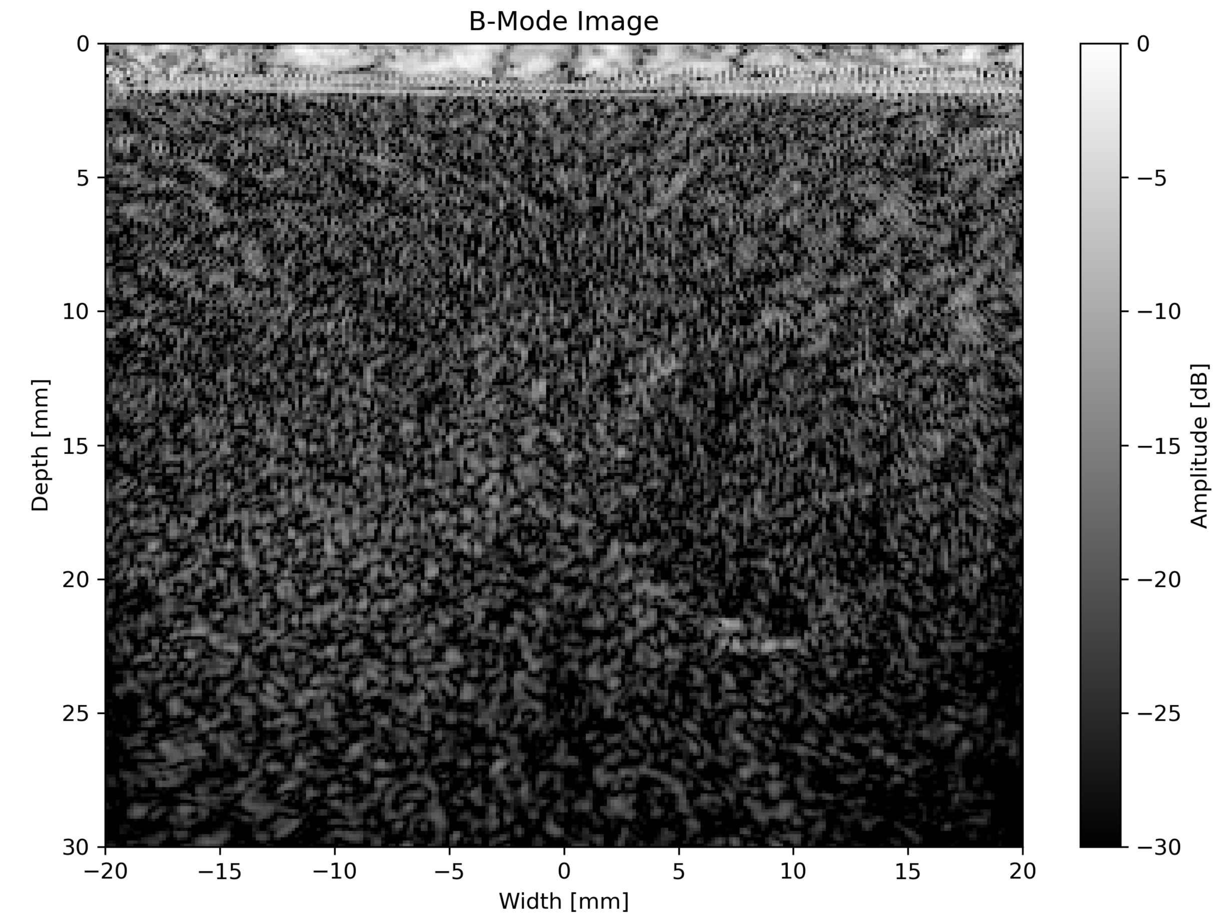

Schema 3: Memory Access




Schema 2: Parallelism

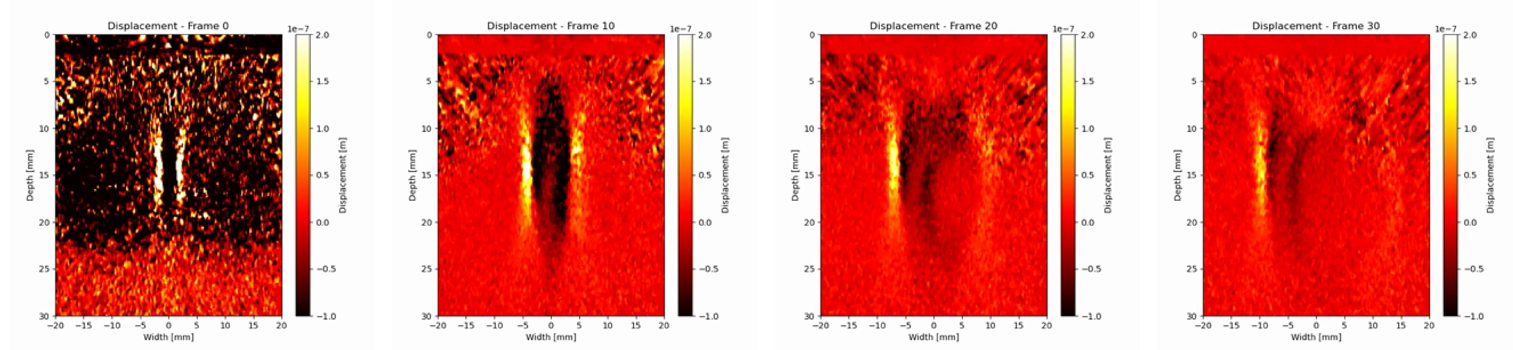

CIRS Phantom

## Results




Reconstructed B-Mode Image

**Wave Propagation**



**Performance Benchmarks** (RTX 3060 vs Ryzen 7800X3D)

| Implementation | Time | Speedup |
|---|---|---|
| CPU (OpenMP) | 1.4375 s | 1.00× |
| CUDA Naive | 0.8025 s | 1.79× |
| **CUDA Optimized** | **0.6500 s** | **2.21×** |

## References

[1] K. Nightingale. Acoustic radiation force impulse (arfi) imaging: a review. *Current Medical Imaging Reviews*, 7(4):328–339, 2011.

[2] USTB. Acoustical radiation force imaging (arfi) from uff file recorded with verasonics. https://www.ustb.no/examples/acoustical-radiation-force-imaging/arfi-from-uff-file-recorded-with-verasonics/. Accessed: 2026-02-09.

[3] USTB. Ultrasound toolbox (ustb). https://bitbucket.org/ustb/ustb/src/master/. Accessed: 2026-02-09.