Analog and Digital Signal Processing for Pressure Source Imaging at 190 MeV Proton Beam

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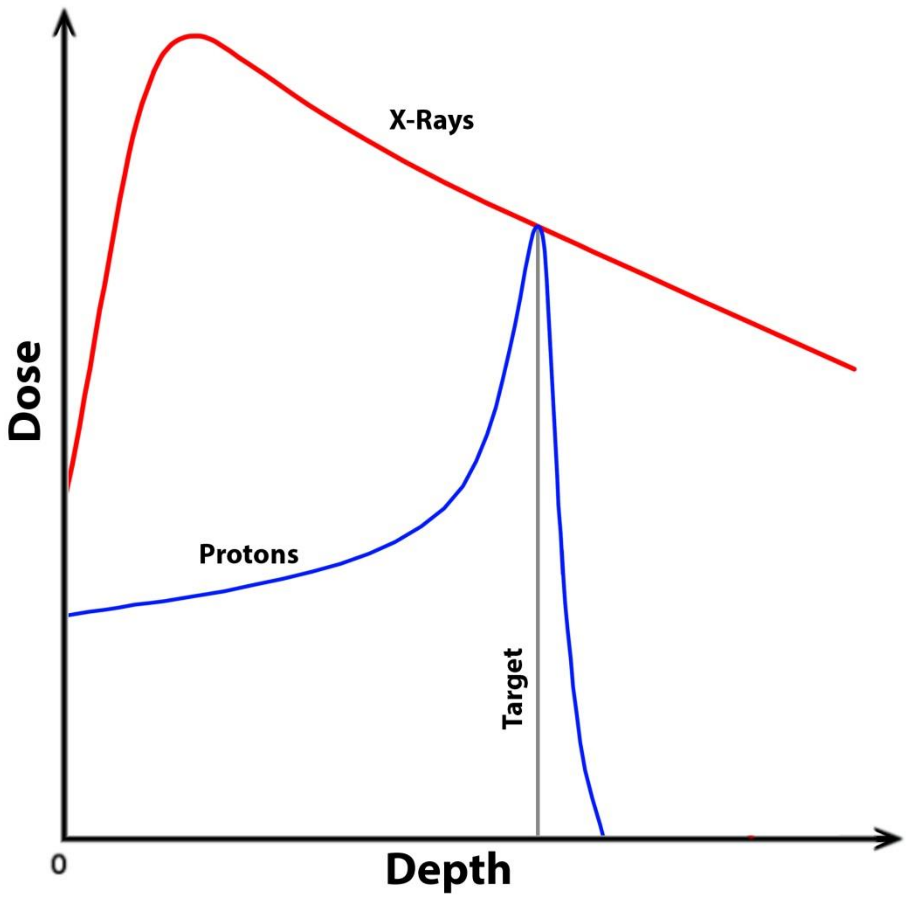
National Institute for Nuclear Physics
Proton Sound Detector Project (ProSD)

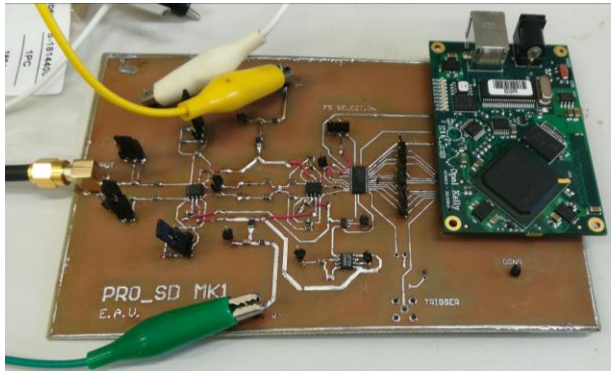
Oncological Hadron Therapy

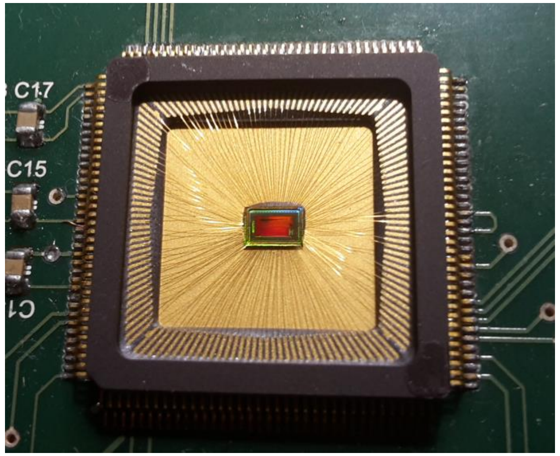


- Utilizes a beam of charged protons or ions to destroy tumoral cells
- Maximum energy deposition on the targeted area
- Reduced collateral dose to healthy tissues surrounding the tumor

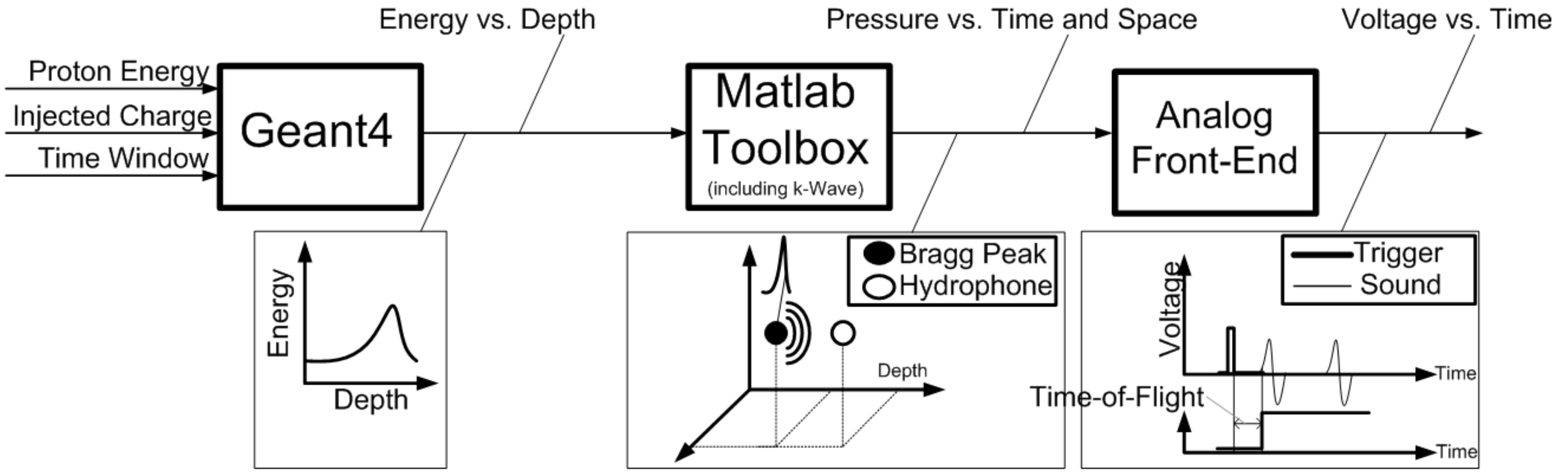
ASIC for Ionoacoustic Experiments

- Ionoacoustic setups lacks advanced/dedicated integrated circuits solutions
  - Target: All Electronics Read-Out in a single Silicon Die
- Advantages of Application Specific Integrated Circuits (ASIC)
  - COST and SIZE → AREA Reduction
  - Low POWER (this releases higher Power for the DSP)
  - Increasing Portability
  - Finally, EASY-to-USE modules
  - Real-Time Detection
- $2mm^2$ for an 8-channel CMOS analog front end
- Low noise, high CMRR, PSRR, low mismatch





Ionoacoustic Proton-to-Voltage Model

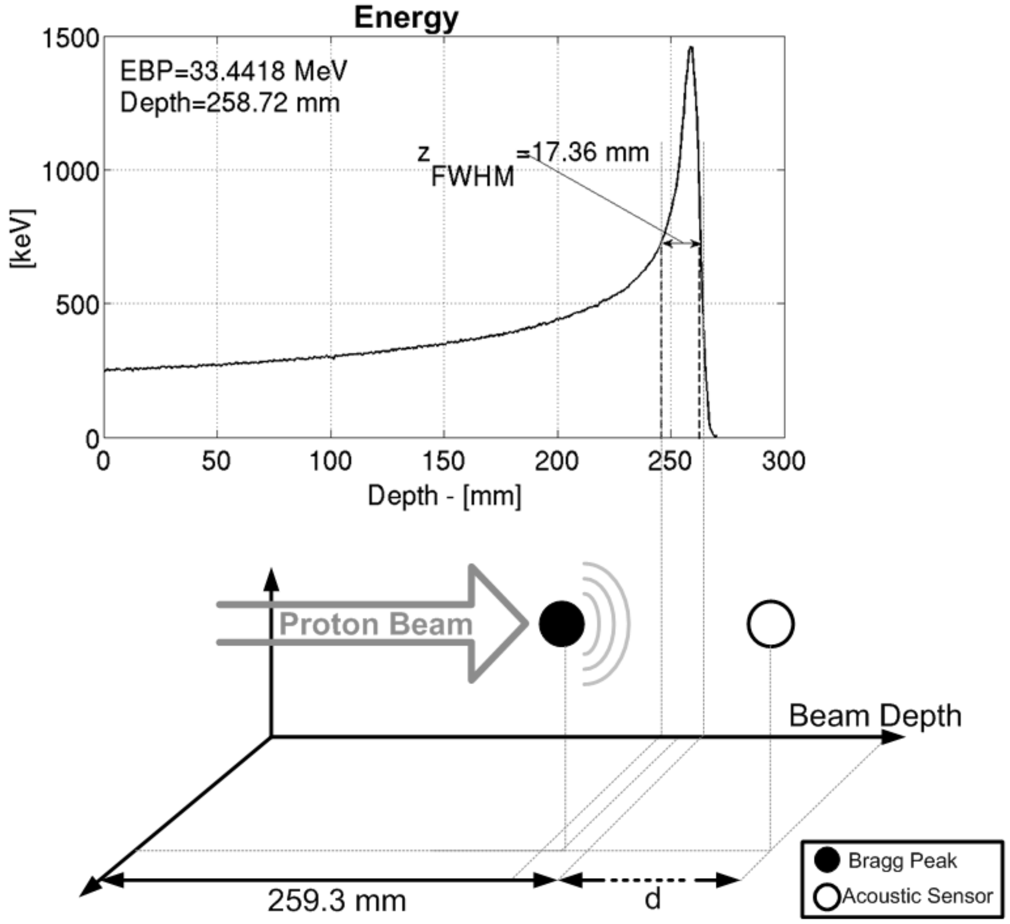


A cross-domain model gives the design parameters for a dedicated ionoacoustic analog front-end (AFE):

- Geant4: extracts energy deposition profile from beam parameters
- Matlab® & K-wave: acoustic wave propagation in water phantom
- Cadence® transistor level AFE model: AFE design, nominal and transient noise simulation

Geant 4 Model for Energy Deposition

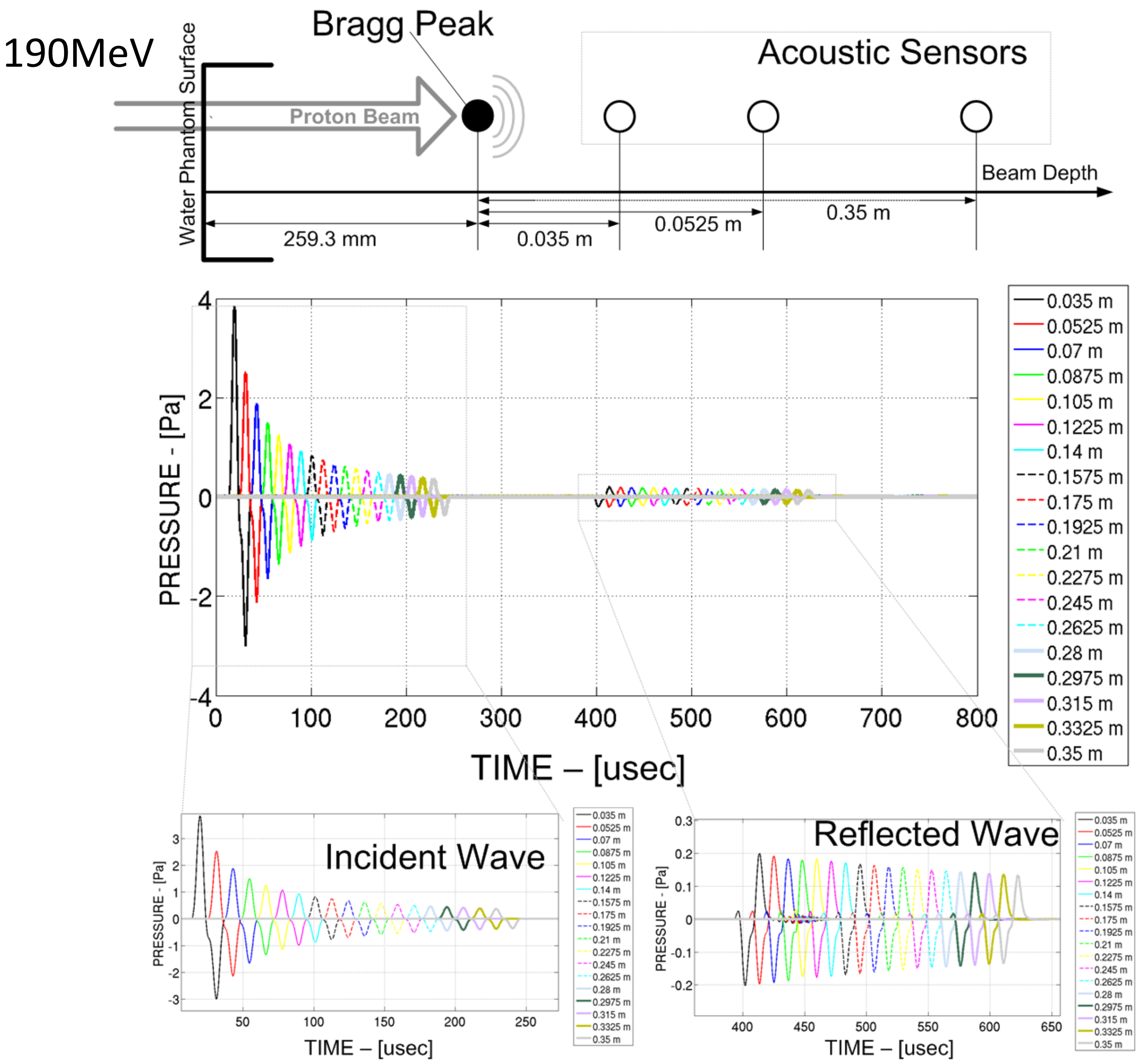
	Parameter	Value
Geant4 Input Parameters	Energy (E)	190 MeV
	Beam Cross Section Area (S_B)	50 mm^2
Geant4 Output Parameters	Deposited Energy Dose (E_{DEP})	1.5mJ
	FWHM Spatial Width (z_{FWHM})	17.36mm
	Beam Depth Range	259.3 mm



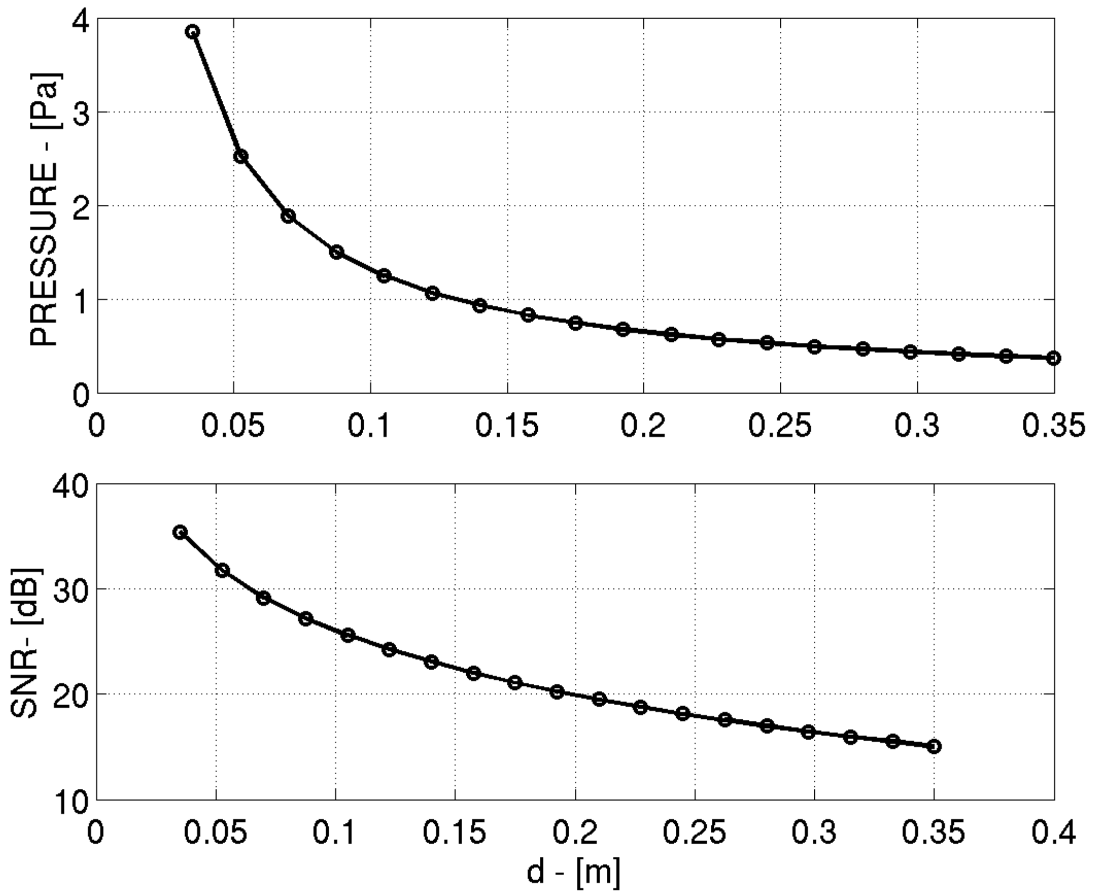
- Geant4 simulations allow to calculate the Beam epth range, BP FWHM and energy deposition
- The estimated pressure increase at the BP is 173Pa

K-Wave Model for Pressure Propagation

- The input pressure at the BP propagates through the medium and can be read-out by specific acoustic sensors (AS) placed at a certain distance d from BP
- The measured signal has a frequency of 42KHz



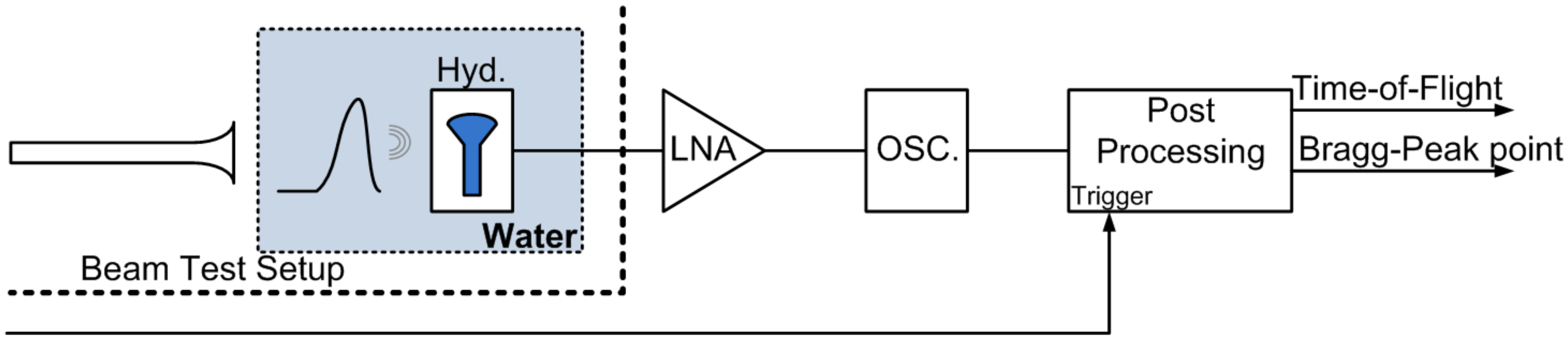
AFE input Signal-to-Noise Ratio



- The sensed pressure level and AS nise power allow to calculate the input Signal-to-Noise Ratio (SNR) for the Ionoacoustic AFE
- A commercial hydrophone data was utilized for this study (*http://www.colmarsrl.com/files/prodotti/ar0190xs-en_48260.pdf*)
- SNR ranges from 38dB (3.5cm from BP) to 15dB (35cm from BP)

	Parameter	Value
Acoustic Sensor	Pass-band Sensitivity	56 µV/Pa
	Pass-band Frequency Range	170Hz-170kHz
	Output Noise Power	3.5µV_{RMS}
	Average Output Noise Power Spectral Density	8nV/√Hz

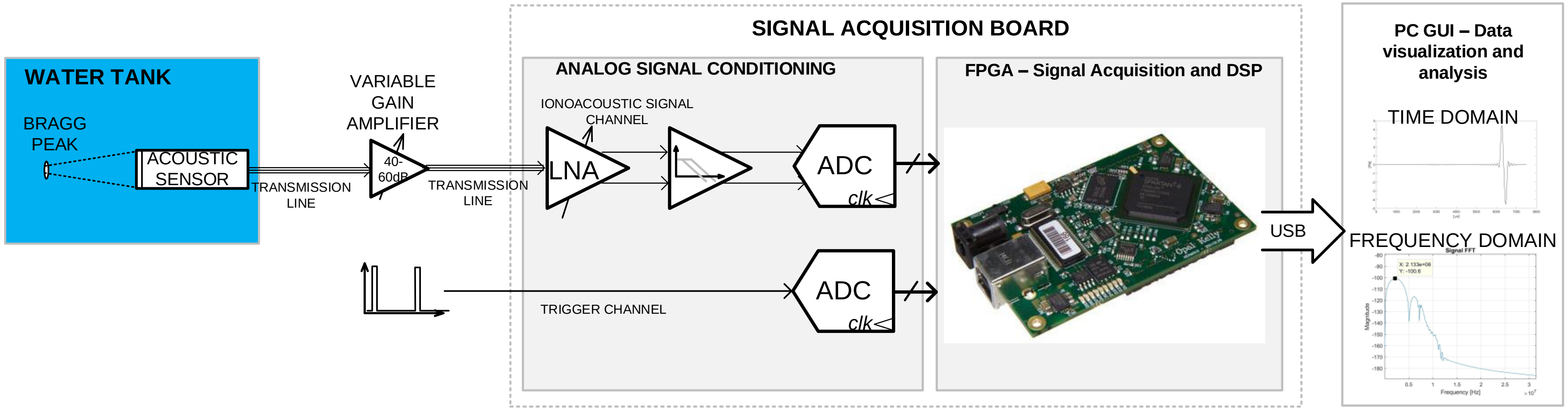
Ionoacoustic Experimental Setup



Ionoacoustic experimental setup composed by:

- 190MeV proton beam
- Water phantom with acoustic sensor
- Low Noise Amplifier
- Oscilloscope for analog signal acquisition
- Post processing stages for Time of Flight (ToF) and Bragg Peak point calculation

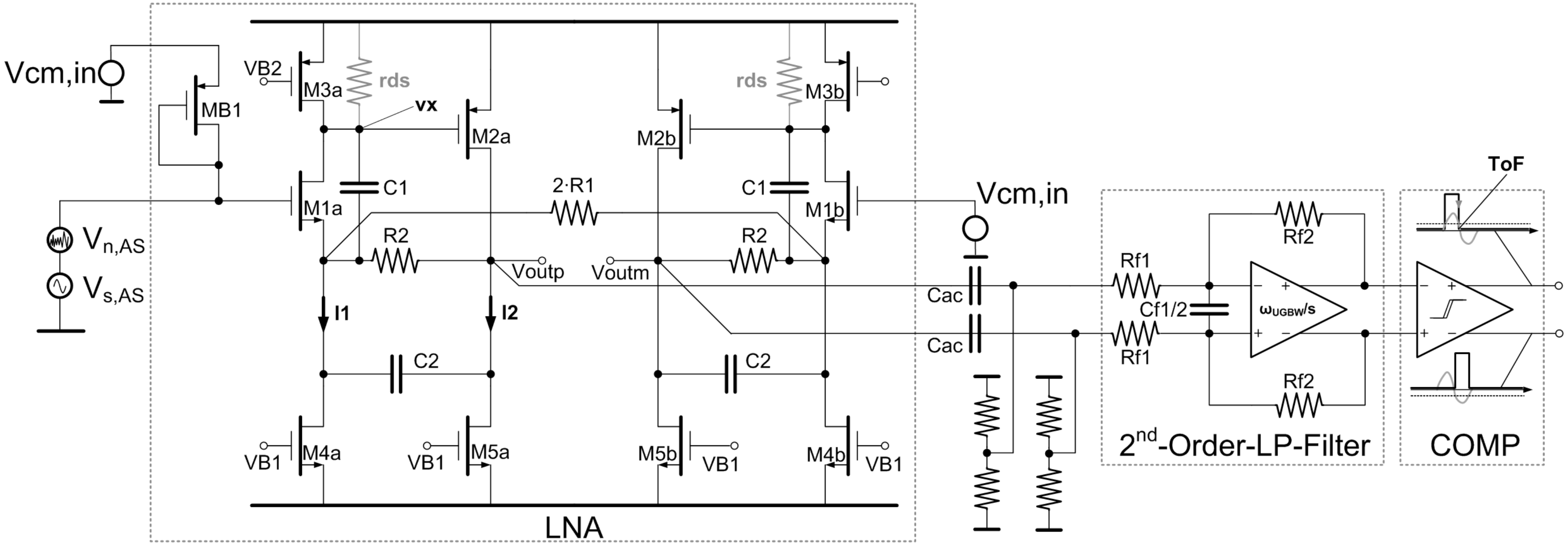
Ionoacoustic AFE schematic



Typical PCB-Based design:

- Ultra-low noise preampifier
- Variable gain amplifier
- Bandpass filter
- Analog-to-Digital Converter

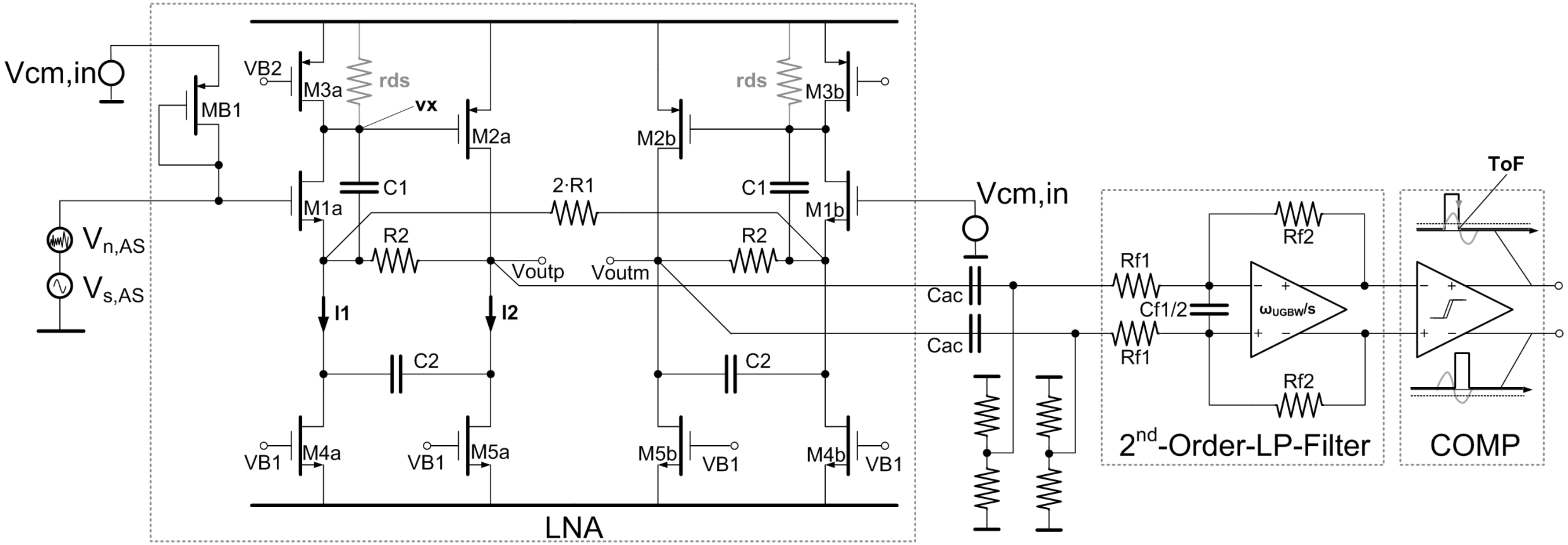
Ionoacoustic AFE schematic



The 0.18µm CMOS proposed ionoacustic AFE is composed by three main blocks:

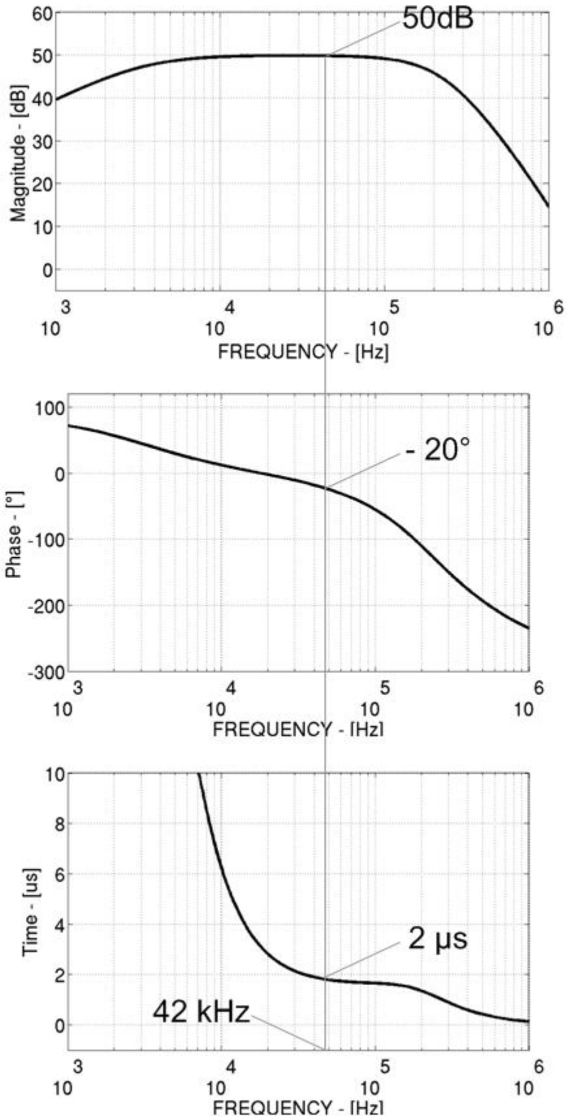
- Low Noise Amplifier (LNA) based on super source follower (SSF) topology
- 2° order Low Pass Filter for out-of-band noise rejection
- Comparator allows to detect the acoustic wave and measure ToF

Ionoacoustic AFE schematic



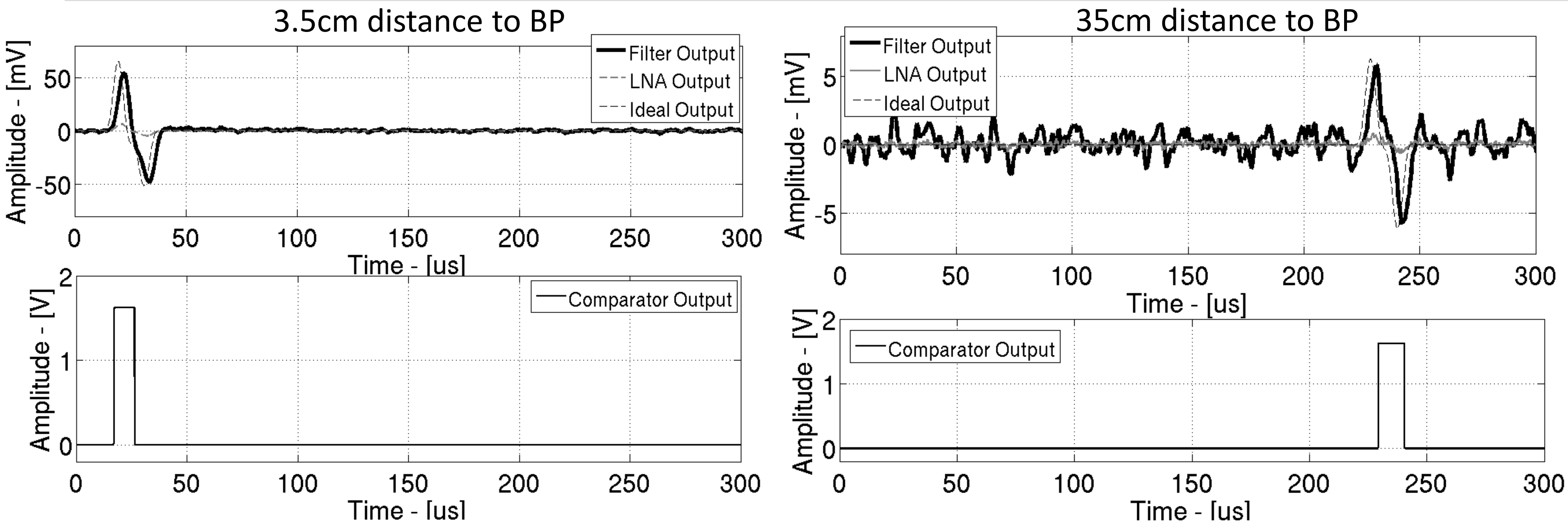
- Around 50dB of amplification are needed for this setup
- Low noise PSD (<8nV/√Hz) and high input impedance (10MΩ) are required to avoid degradation of the input signal →→→ Gate input node
- SSF allow high input impedance and low power consumption compared to classical opamp-based solutions
- Gain is spread all over the chain with a 30dB gain LNA and a 20dB gain Active-Gm-RC LP filter

AFE frequency response analysis



- Magnitude, Phase and Group delay frequency response are extracted from Cadence® transistor-level simulation
- In-band gain of the AFE is 50dB
- Group delay estimation is very important in this scenario since it could lead to systematic error in ToF measurement
- At 42KHz gruup delay is 2μs

AFE output signal

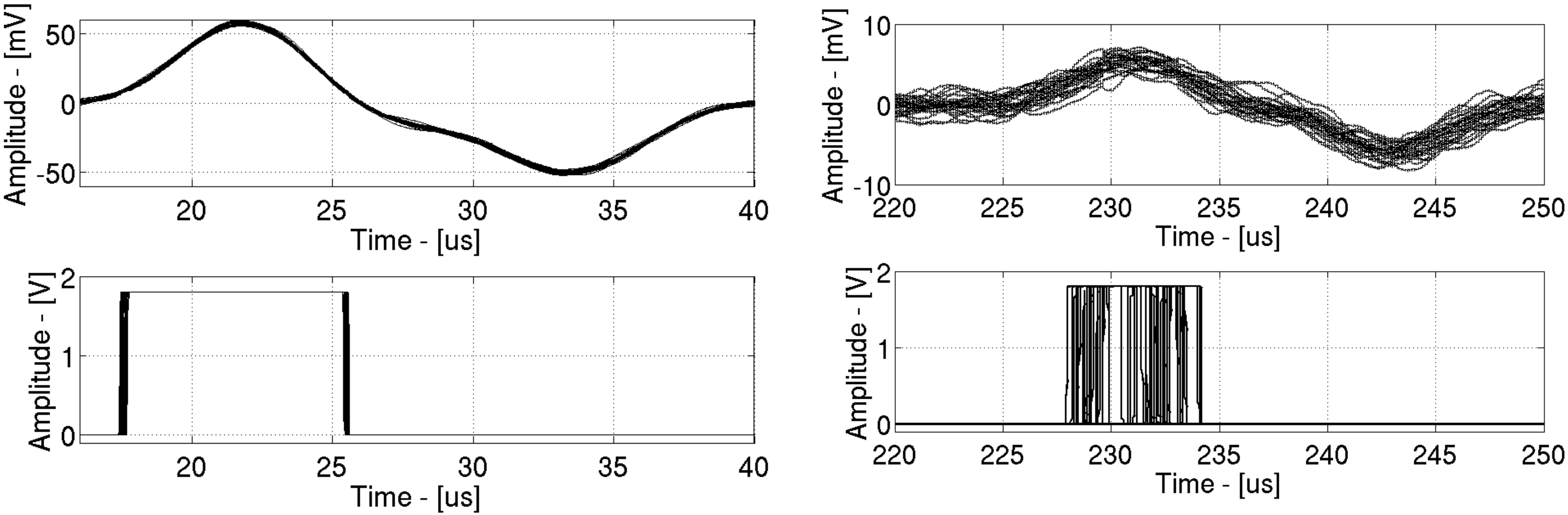


- The comparator output is at ‘1’ logic level if the input signal is above 3-sigma of the noise floor

→Simple single-bit way to calculate ToF

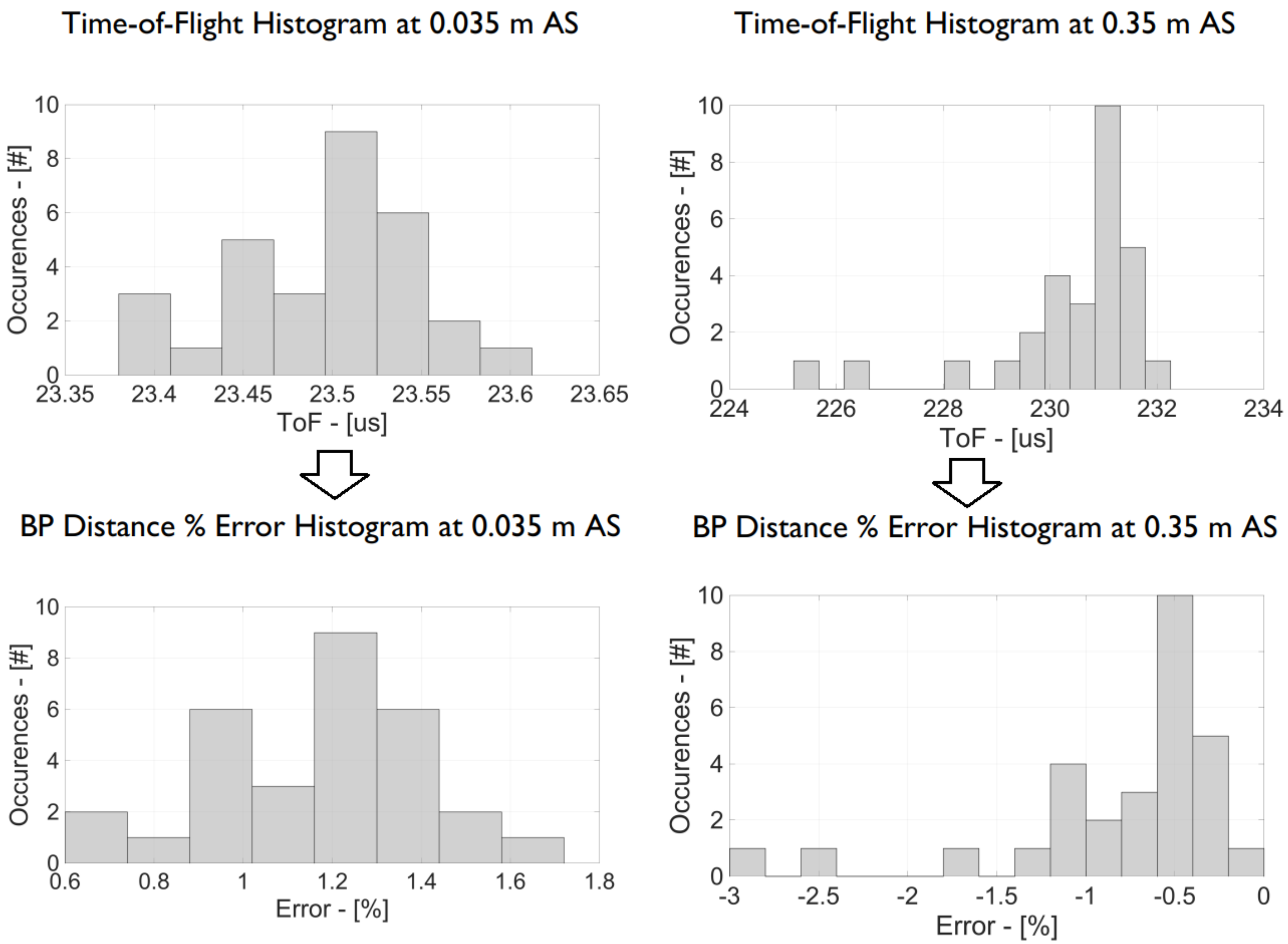
→Reduces number of output pins for multichannels board while keeping all the necessary information

AFE ToF Estimation



- Multiple transient-noise simulation allows to estimate the ToF in presence of noise

AFE ToF Estimation



- After compensating for the 2μs delay caused by group delay effects at 42KHz, the BP distance was calculated from the ToF
- Average error is 1% and 1.2% for 3.5cm and 35cm respectively

→±0.35mm for the 3.5cm AS

→±4.2mm for the 35cm AS

Conclusions

- A complete design of a low-noise acoustic analog-front-end for Bragg-Peak detection by acoustic waves sensing has been presented

- The input signal for the AFE has been obtained by mixed-signals simulations developed by Geant4 and k-Wave for proton beam and acoustic energy, respectively

- The AFE has been then validated by both nominal and transient noise simulation, resulting in 1.2% average BP detection error for the farther acoustic sensor

Thank you for your attention!

Q&A