Pulse-Echo Ultrasound Brain Imaging

Design Document

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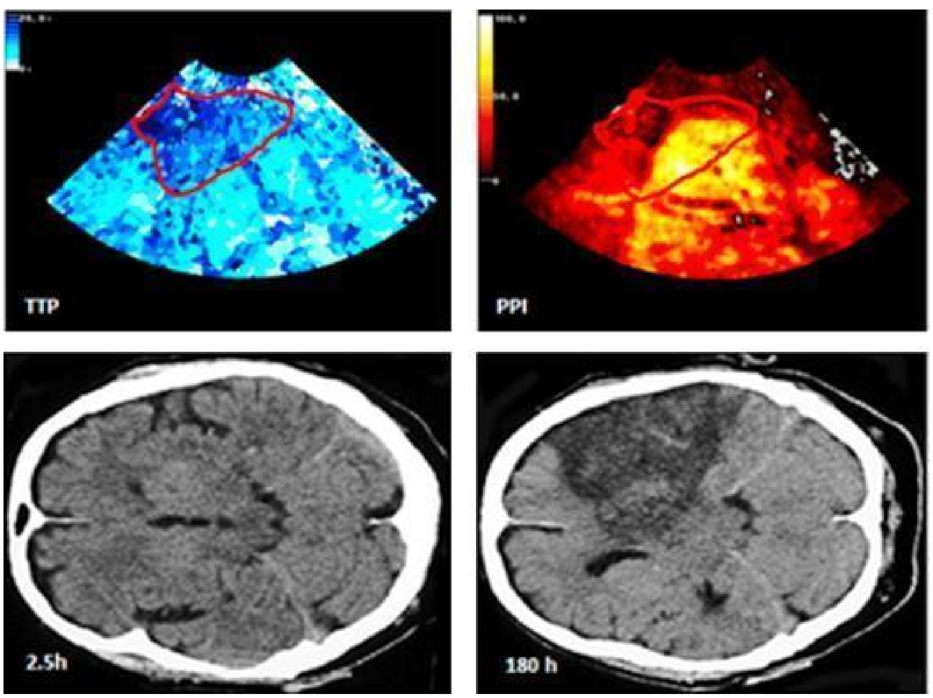

http://www.sciencedirect.com/science/article/pii/S2211968X12000484

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Executive Summary

The goal of this project is to expand upon a previous group's design for a pulse echo ultrasound system for brain imaging, which could be used as a low cost alternative to fMRI. The following report will contain the design for a transmission circuit and a receive circuit for the ultrasound system. The transmit circuit will be able to send high voltage pulses (+/-50V) over 8 channels (scalable to 512) to a transducer. The receive circuit will then receive the signals from the transducer and amplify them before sending them to a computer interface.

System Requirements

Our goal is to design and build a transmit circuit capable of sending +/-50V pulses over 8 channels (scalable to 512) to send to a 512 element transducer our client had previously bought. The circuit should then be capable of receiving low voltage pulses back from the transducer and amplifying them to send to the National Instruments DAQ system. To reduce costs our client wants us to demultiplex the signal from 512 channels to 128 channels before sending it to the National Instruments system.

<u>Functional</u>

- Transmit 8 channels at 1 MHz
- Receive 8 channels
- Generate +/- 50 V bipolar pulses
- Protection for the receive circuitry
- Protection circuit for the computer interface (Max allowed 2 Vpp)
- Variable gain for differing imaging depths
- Total Gain of 70 dB

<u>Non-functional</u>

- Maximum 60 in^2 boards (to reduce cost and complexity)

System Overview

We have divided our current design into three separate parts; transmit circuit, receive circuit, and the computer interface. The transmit and receive circuits are based on our own research and suggested ultrasound hardware provided on the Texas Instruments website. A block diagram of the suggested Texas Instruments design can be seen below:

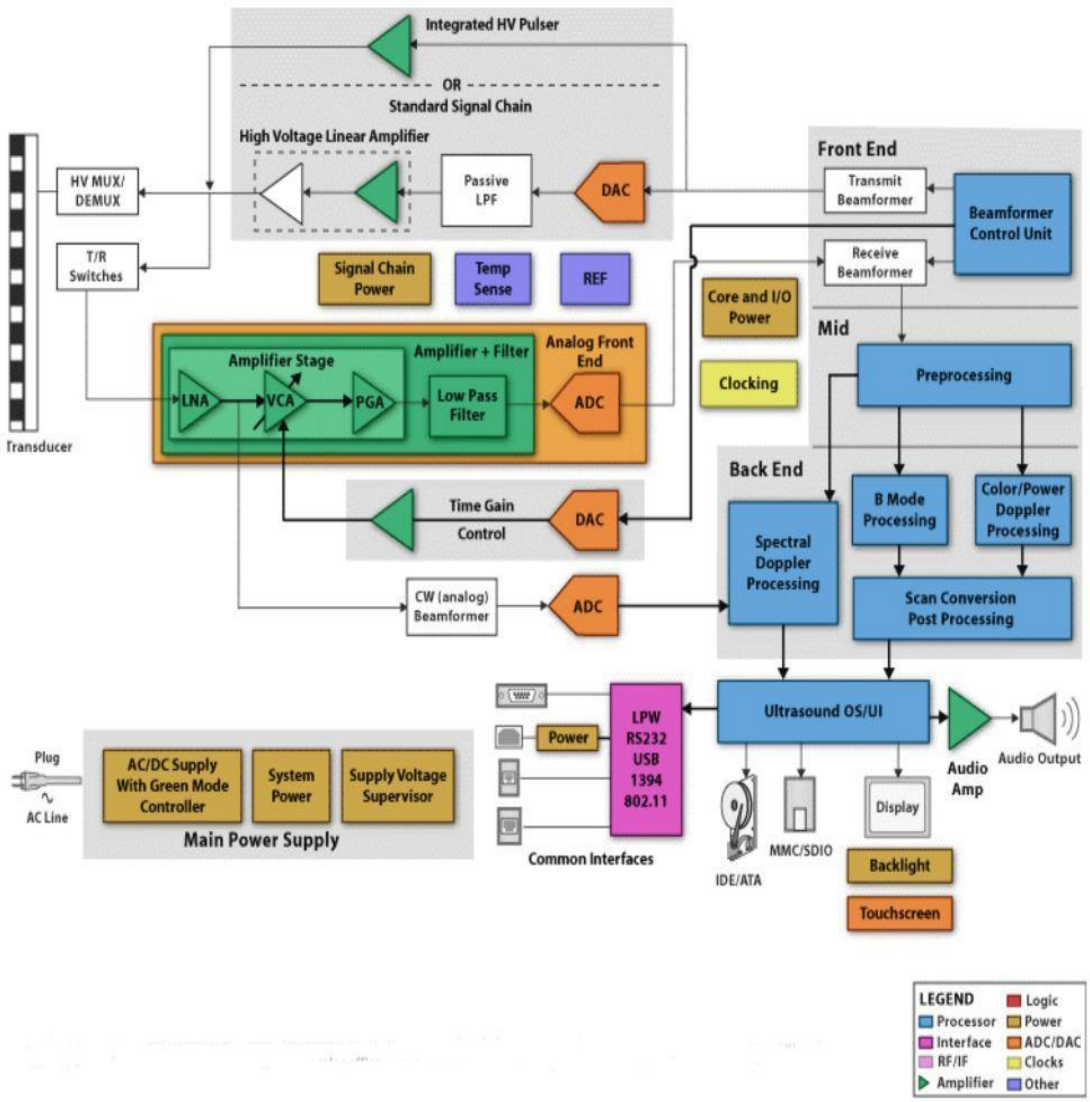

Figure 1:Texas Instruments block diagram

Transmit Circuit:

The transmit circuit will be responsible for sending +/-50V pulses to the transducer, using the LM96570 (beamformer) and LM96550(high voltage pulser). The control of the beamformer, and thusly the entire transmit circuit, is delegated to a National Instruments system specifically designed for use in ultrasound. The previous group's design used high voltage pulsers, which were controlled by being connected directly to a computer interface and needed 18 control bits to be able to send pulses over 8 channels. To help keep costs down we decided to implement Texas Instrument's suggestion of using the LM series combination of the LM96570 and LM96550. The addition of the beamformer IC allows us to control the pulser using a serial interface, which reduces the required control bits from 18 down to 9. Below is a block diagram representation of the transmit circuit:

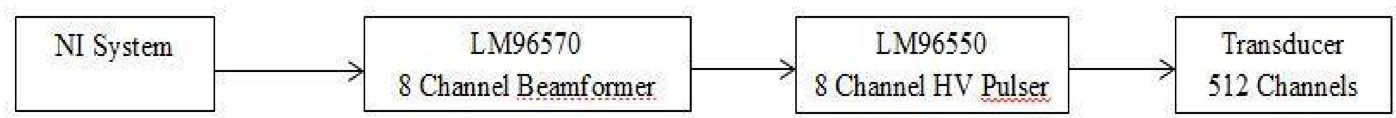

Figure 2: block diagram of Transmit Circuit

Receive Circuit:

The receive circuit will be responsible for receiving the low voltage signals sent back by the transducer. The receive circuit will amplify signal before sending the information back to the computer interface. The receive circuit contains the TX810(T/R switch), the LMH6622 (Low Noise Amplifier or LNA), and the protection circuit of our own design. The TX810 is responsible for blocking out the outgoing 50 V pulses and receiving only the return signal from the transducer. It also limits the output voltage of the transducer to $2V_{pp}$. The low noise amplifier stage of the receive circuit is responsible for amplifying the low-voltage signal received back from the transducer. The protection circuit limits the signal out of the low noise amplifiers and into the NI 5752 to 2 V_{pp}. Below is a block diagram representation of the receive circuit:

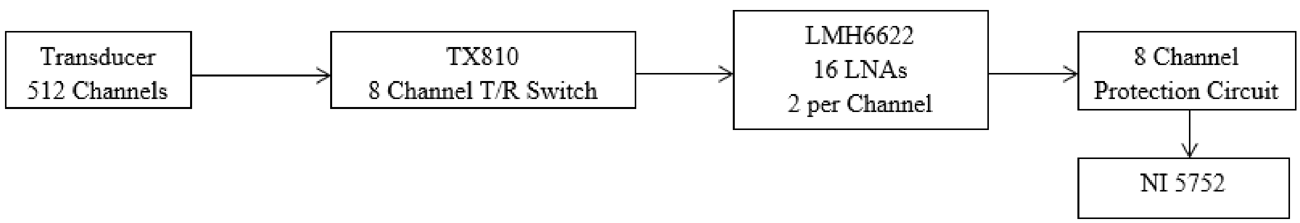

Figure 3: block diagram of Receive Circuit

Computer Interface:

To control our circuit we are going to be using a National Instruments PXI system which will be capable of sending control signals to our transmit and receive circuit. The National Instruments PXI system will contain the NI-5752 module, which contains a variable gain amplifier and analog to digital converter.

Overall System Block Diagram:

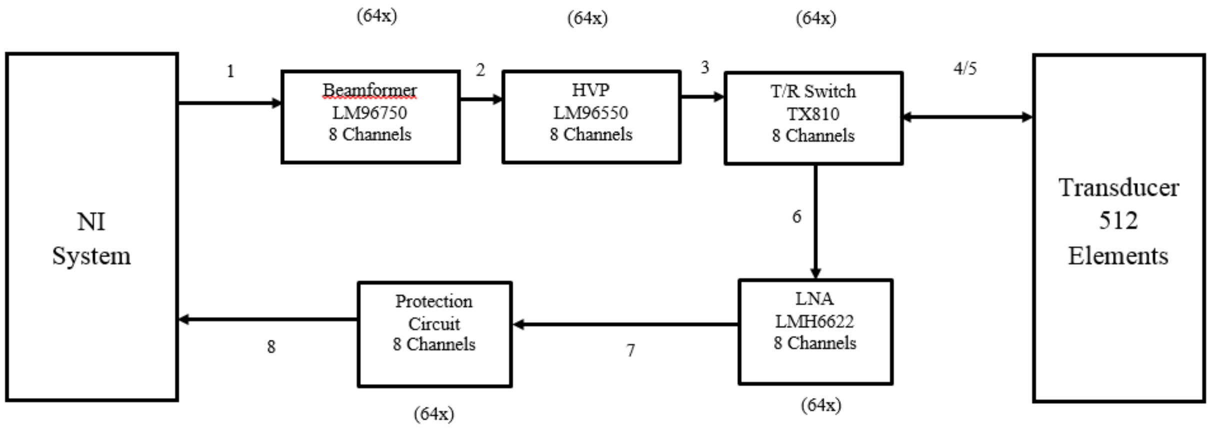

Figure 4: Overall block diagram

Detailed System Design

Transducer:

The transducer is the part of the system that will come in contact with the patient. It is able to receive a high voltage pulse which it then converts into an ultrasonic pulse at a pre-determined frequency. The ultrasonic pulse is then sent into the body and the reflected pulses are captured by the transducer and converted into electrical signals that can be processed to form images. We will be using a 512 element transducer in our design.

Computer Interface System:

We will be using the National Instruments PXI System to receive the signals back from the transducer and to control our high voltage pulser. The PXI system has a modular design which allows us to use different boards based on our needs. Our team will use the NI PXI-7813R Virtex-II 3M Gate R Series Digital RIO Module to send control signals to the Beamformer. For the receive circuit we will be using the NI 5752 board.

NI PXI-7813R:

Parameter	Specification	Required Specification
Digital Control Signals	160 bits (will need 2)	320 bits (64*5)

Table 1

NI-5752:

Parameter	Specification	Required Specification
Receive Channels	32 channels (we will need 4)	128 channels

Table 2

Beamformer:

The Beamformer connects directly to the high voltage pulser and reduces the amount of digital signals needed to control the high voltage pulser from 18 to 9 channels.

We will be using the Texas Instruments LM96570 Transmit Beamformer. It offers eight output P and N channels at an individual delay from .78 ns to 102.4 µs at a max pulse rate of 80 MHz. The National Instruments PXI system will send five control bits to the Beamformer which will then interpret these control bits and send the appropriate signal to the high voltage pulser to create a high voltage pulse over each of the 8 channels. The LM96570's datasheet should be referenced for a more detailed explanation on how this works.

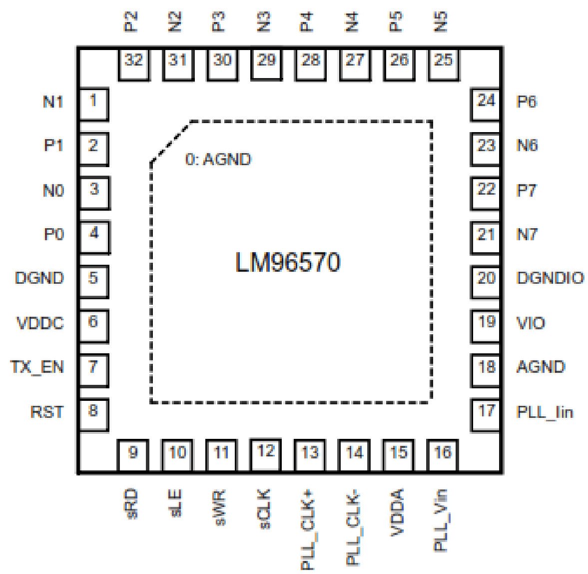

Figure 5 : LM 96570 Pin layout

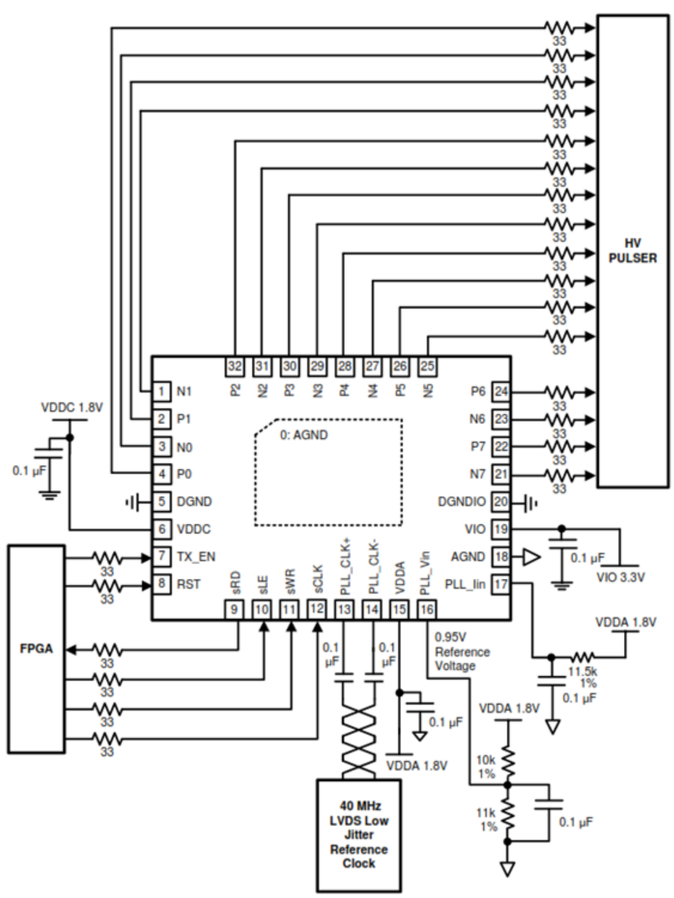

Figure 6 : Reference Circuit

High Voltage Pulser:

The High Voltage Pulser is the component of our system that will generate the excitations of the transducer. These excitations will be in the form of both positive and negative square pulses. It will be controlled by the LM96570 Beamformer.

We will be using the Texas Instruments LM96550 Ultrasound Transmit Pulser. As you may notice in the following table, we desire 512 channels of operation, but the LM96550 supplies only 8. Therefore, we will be using 64 pulsers in conjunction with one another to achieve the desired 512 channels.

Parameter	LM96550 Specification	Required Specification
Voltage Output	+/- 50 V	+/- 50 V
Frequency Range	Up to 15 MHz	1 MHz
Number of Channels	8	512 (8x64)
Switching Delay Time	32 ns	Less than 167 ns

Table 3

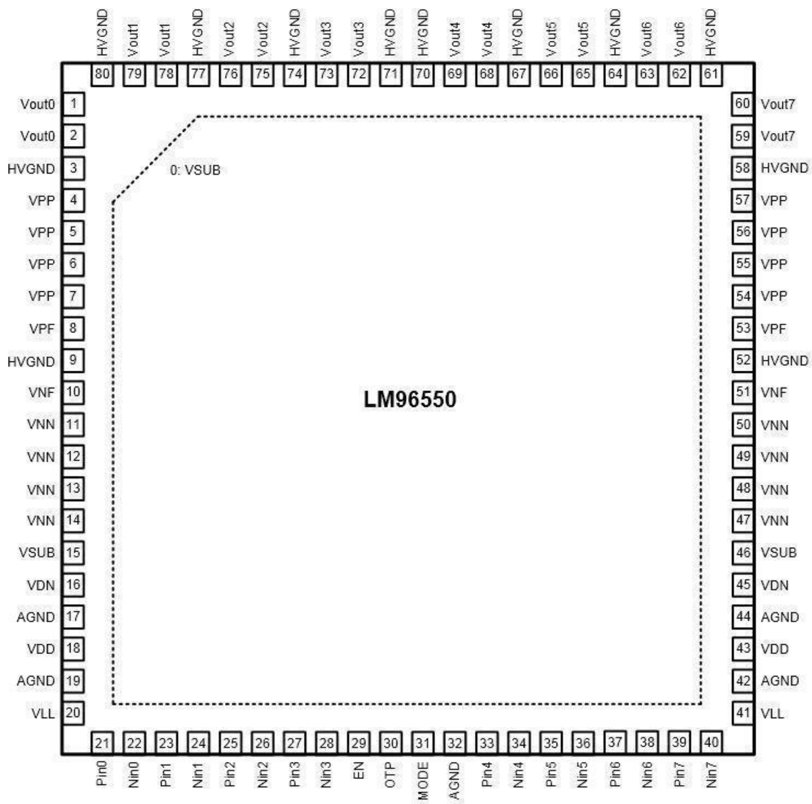

Figure 7 LM96550 Pin Layout

The pulser will only operate when the EN pin is driven HI. If the pulser is enabled, driving PIN or NIN HI will generate a positive or negative pulse, respectively, at Vout. Vout will be pulled to the positive supply (VPP) or the negative supply (VNN) by power MOSFETs. If both PIN and NIN are LO the output Vout will be pulled to GND (0 V). It is important to never drive both PIN and NIN HI as this will cause damage to the circuit the LM96570. The following figure is a block diagram of a single channel of the pulser.

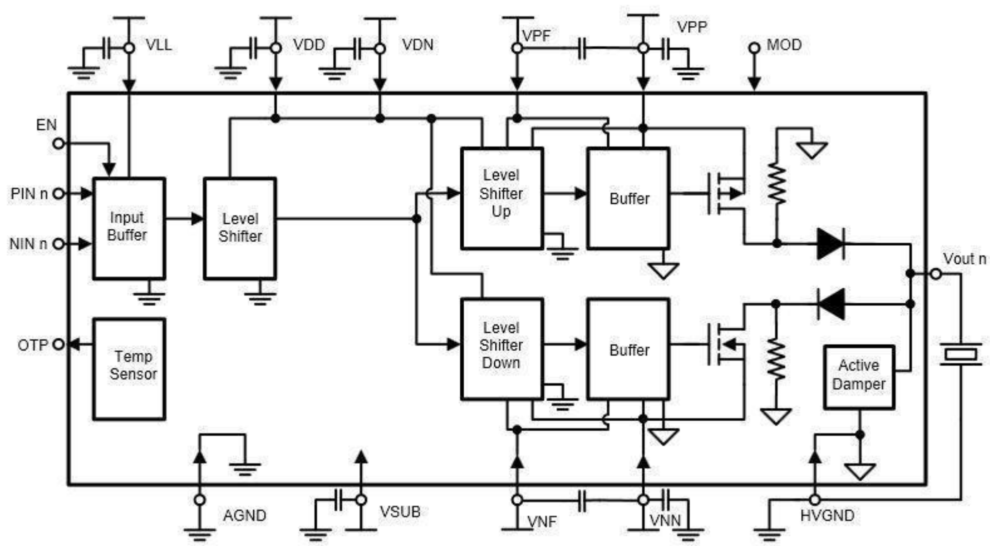

Figure 8 : Block diagram of single LM96550 channel

T/R Switch:

The T/R switch will act as an interface between the transmit and the receive sides of our system. It will allow high-voltage signals from the High Voltage Pulser to be passed to the transducer in the transmit stage, while limiting the output voltage to the receive stage to only 2Vpp Thus, the T/R switch's primary purpose is to act as a buffer between the system's Low Noise Amplifiers and the High Voltage Pulser as the Low Noise Amplifier can be permanently damaged by high voltages.

We will be using the Texas Instruments TX810 part in our system. The TX810 supports 8 channels and has three digital control bits (B1, B2, and B3) that determine its biasing current; increasing the biasing current decreases the switch's impedance. Some properties of the system may be optimized by introducing different values of load inductance and resistance, but this may also lower the system's sensitivity.

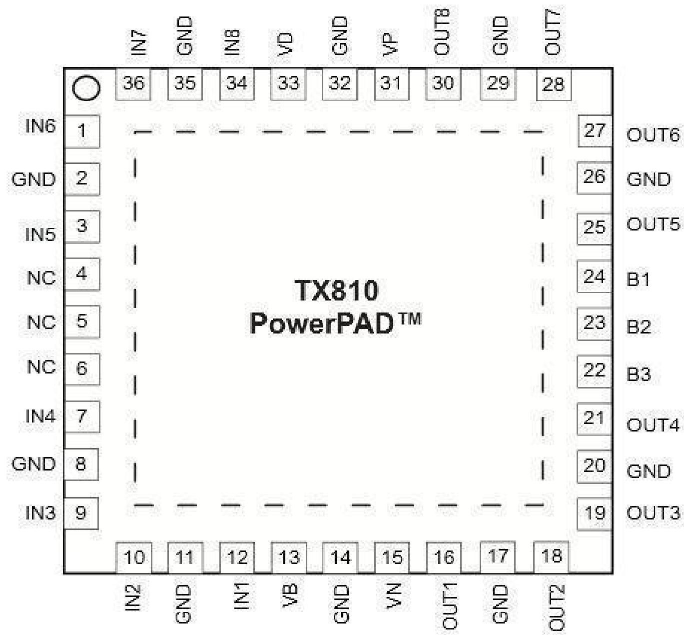

Figure 9 : TX810 Pin Layout

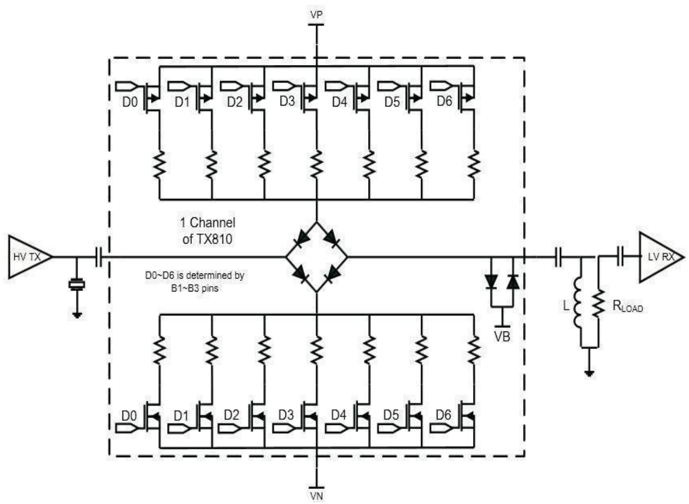

Figure 10 : Block diagram of single TX810 channel

Low Noise Amplifier:

The low noise amplifier amplifies the heavily attenuated, reflected signals from the transducer which have been transmitted through the T/R switch (TX810) such that the signals can be sampled and processed for imaging.

For the low noise amplifier we chose to use the LMH6622 from Texas Instruments. For our design our client estimated we would need to have 40dB worth of gain before sending the receive signal to the NI-5752 device. He was also looking for a 3dB bandwidth around 10MHz to accomplish this we decided to use two LMH6622 amplifiers in a cascaded setup. The reason for this was so that we could reach the required gain of 40dB and still have a 3dB bandwidth for each amplifier of at least 10 MHz.

Parameter	LMH6622 Specifications	Required Specification
LNA Gain	N/A	40dB
3dB Bandwidth	N/A	10MHz
Gain Bandwidth	120MHz	N/A

Table 4

For our amplification circuitry we implemented a two stage amplifier, each stage using a non-inverting configuration producing a gain of 20 dB.

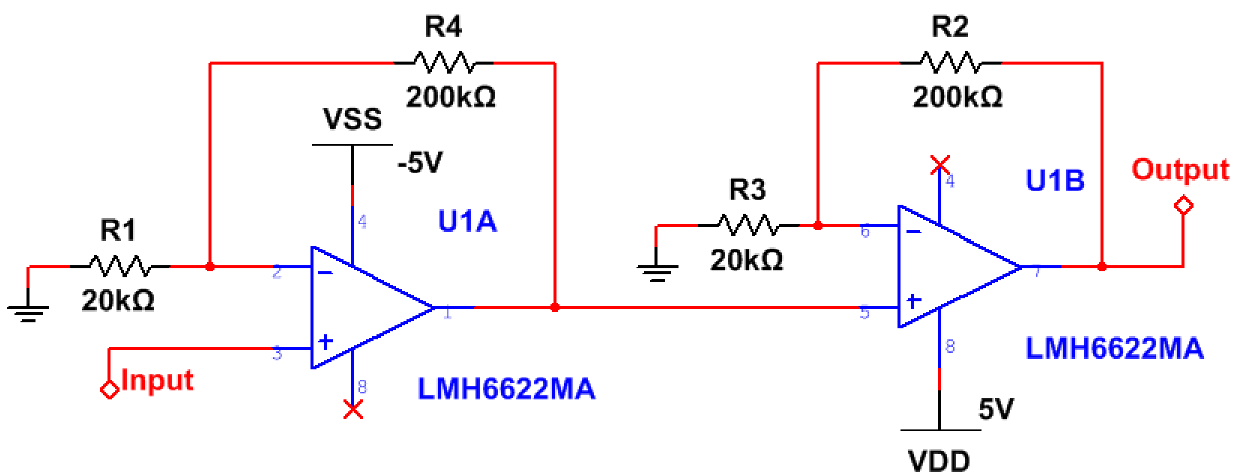

Figure 11: Amplifier Design

Board Break Down

To save money and reduce complexity our group plans on limiting ourselves to 2-layer 60 in^2 boards for all printed circuit designs. The reason for this is that senior design groups at Iowa State receive a discount on printed circuit boards under 60 in^2. To accomplish this task we plan on dividing our circuit up into separate groups as follows:

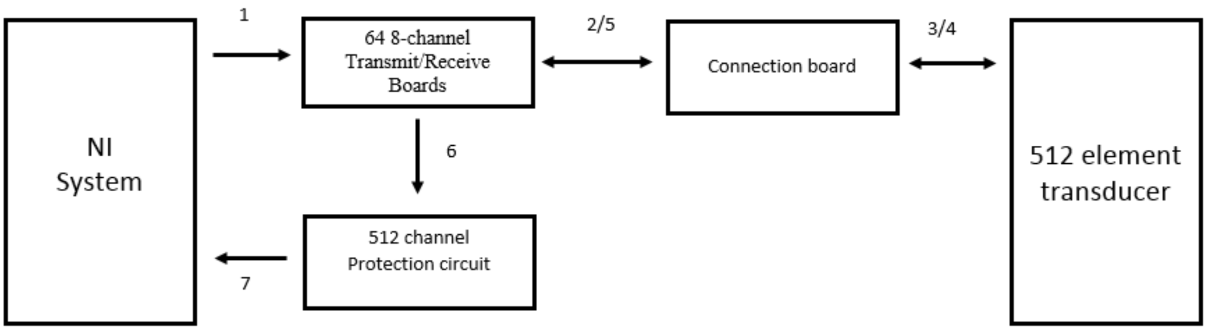

Figure 12: Board Break Down block diagram

Board	Estimated Number of Boards for 512 channels	Number of channels per board
Transmit/Receive Board	64	8-channels
Connection board	2	256-channels
Protection Circuit	16	32-channels

Table 5

Transmit/Receive Boards:

The transmit/receive boards are responsible for transmitting the high voltage pulses to the transducer, and also receiving back the low voltage signal from the transducer. After receiving the low voltage signal from the transducer the circuit will amplify the low voltage signal before sending the amplified signal to the protection board. Below is a breakdown of how many parts will be needed for each 8 channel board.

Device	Number of Devices per Board; 64 Boards Total
LM96550 (HVP)	1
LM96570 (Beamformer)	1
TX810 (T/R Switch)	1
LMH6622 (LNA)	8

Table 6

Connection Board:

The connection board connects the 8-channel transmit/receive board to the transducer. The 512-channel transducer uses two 256 pin connectors to connect to the board, each connector should be on its own board. The high density of the connectors require that each board be at least 6-layers in order to properly connect each pin.

Protection Circuit:

The protection circuit is used to protect the receive circuitry from voltage spikes that could damage NI 5752 module.

Parameter	Required Specification
Voltage Limit	2 Vpp
Operation Frequency	1 MHz
Gain Bandwidth	N/A

Table 7

Below is the schematic for the precision bounding circuit we used to accomplish this task.

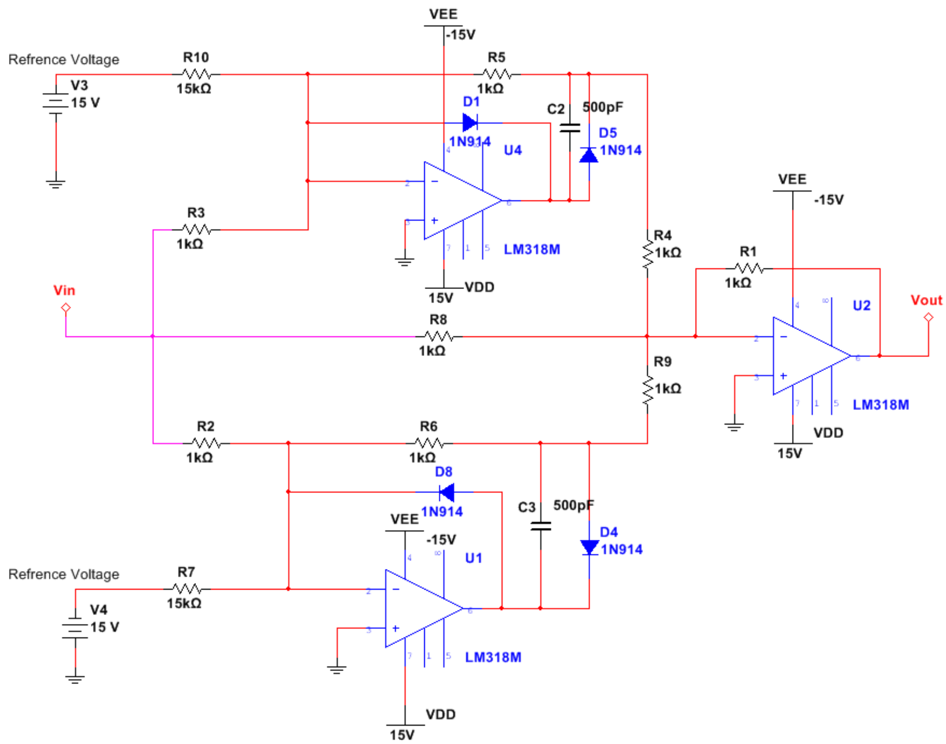

Figure 13 : Protection Circuit Schematic

The circuit is controlled by the two reference voltage supplies (Vref) and two resistors(R7 and R10), in this case a +-5 V supply. We picked the reference voltage to match the supply voltage for the LM318M to simplify the design. The upper limit of the output is determined by the ratio Vref/R10 and the lower limit is determined by the ratio -Vref/R7. Below is a graph of a DC sweep of the input voltage from -6 V to 6 V:

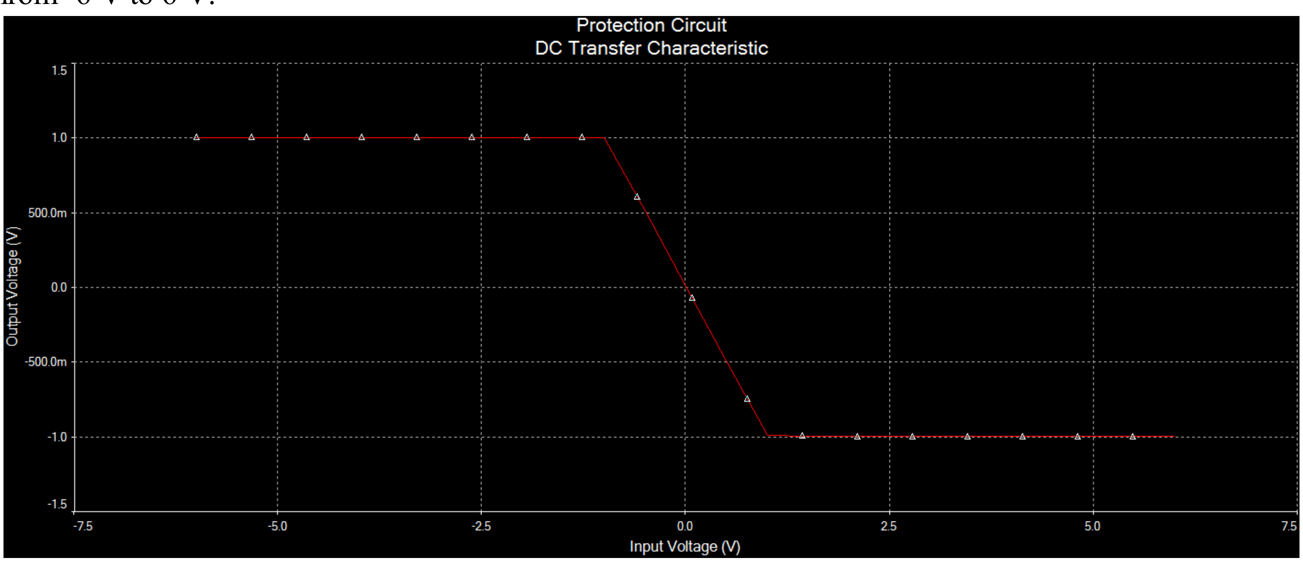

Figure 14 : Protection Circuit Input Output Characteristics

From the above graph one can see that when the input is higher than 1 V the output is limited to 1 V and when the output is lower than -1 V the input is limited to -1 V.

The next two graphs show the simulations for the protection circuit at 1 MHz. The first graph shows a signal of 2Vpp passing through the circuit with minimal attunations as desired. The second graph shows an input signal of 5 Vpp (this is the max voltage that could be passed by the LNAs), being attunated to below 2Vpp as desired.

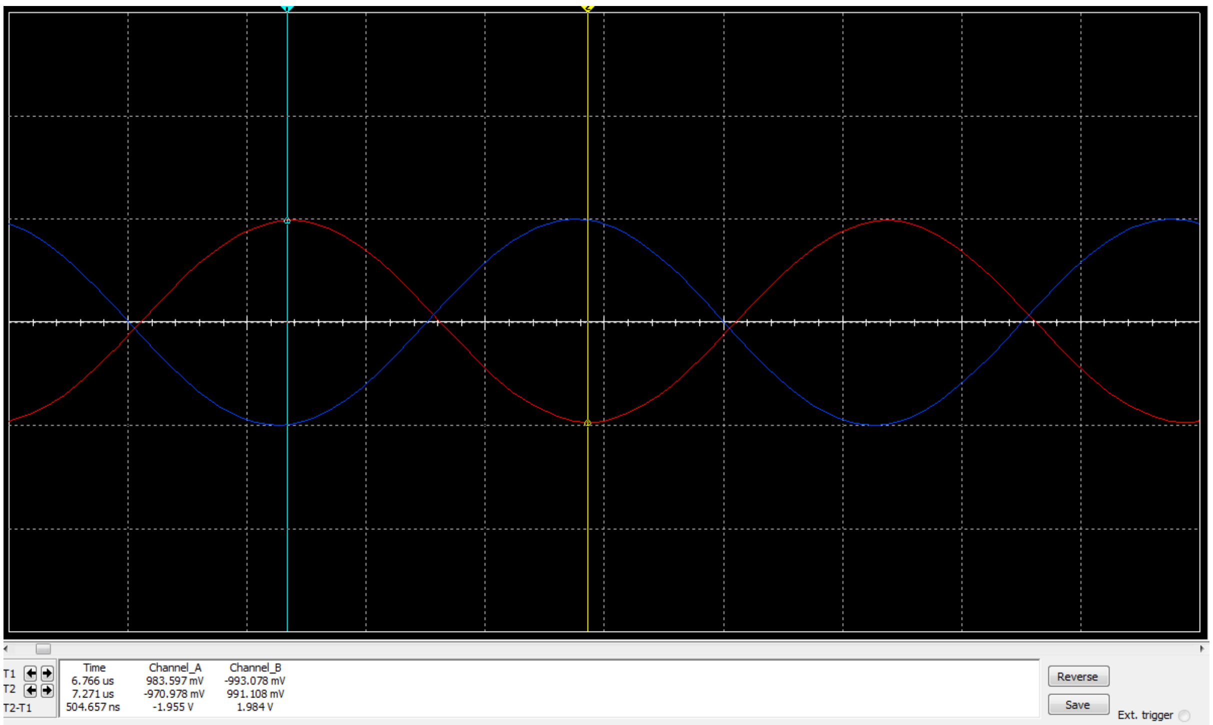

Figure 15: Input=2 Vpp Output=~1.98 Vpp

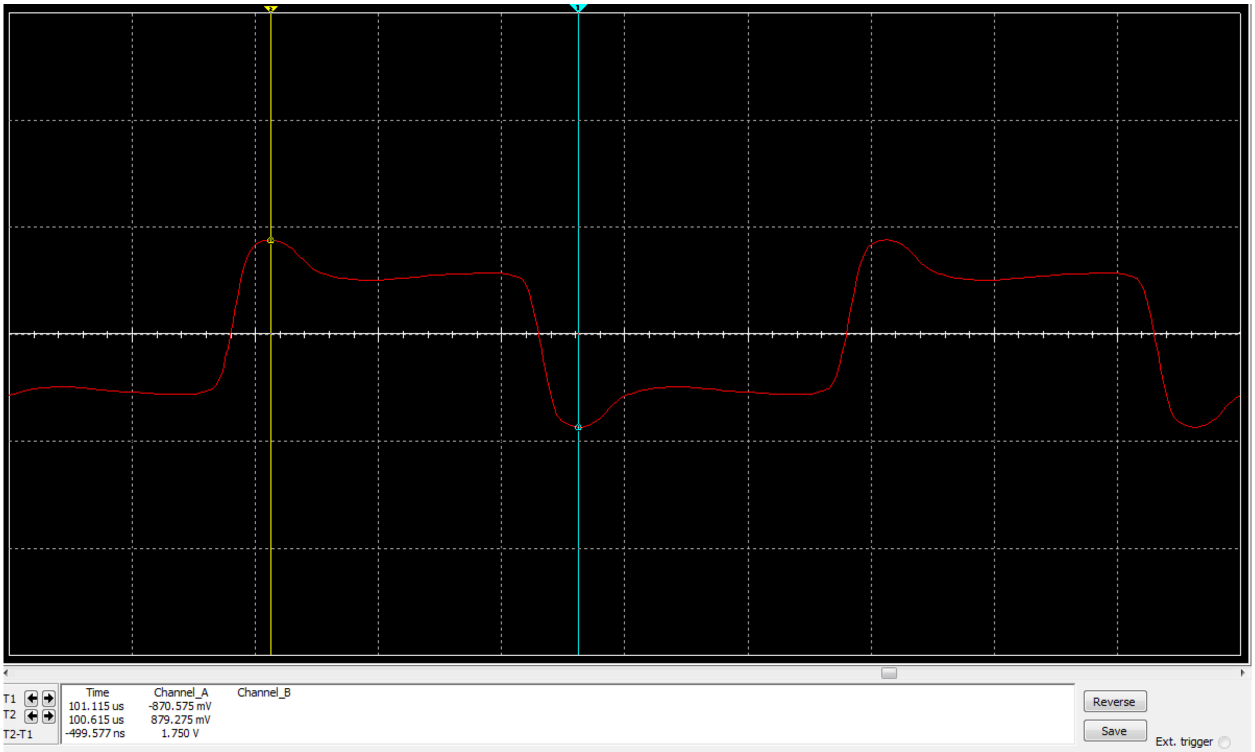

Figure 16: Input= 5 Vpp Output=~1.750 Vpp

Challenges Encountered

- New to PCB design and PCB design tools
  - None of our group members had previous experience with Multisim, Ultiboard, or PCB design. All of which were heavily used for this project.
- Understanding the previous group's work
  - We are continuing a previous senior design team's work, and therefore had to put in a large amount of effort to understand their work and design. We also had to change a fair amount of their design in order to comply with updated requirements.
- Finalizing our part set
  - We spent a large amount of time in choosing our parts. Initially we changed our high voltage pulser from a Hitachi part that the previous group had chosen to the current TI part, and ultimately, we chose an entirely new series of (TI) parts.
- Soldering small high density ICs
  - Pin bridging because of high density ICs

Testing

Our group tested an 8-channel test board containing the LM96570, LM96550, TX810, and eight LMH6622 chips. We wanted to show that we can both send and receive a signal using our planned chip set. We also wanted to make sure our circuit is compatible with the National Instruments system our client plans to order. Thus, we have designed our circuit to connect directly to the National Instruments system.

Protection circuit :

A large amount of time was spent analysing and simulating the protection circuit. Though the circuit appears to be quite simple, its analysis was ultimately quite complex; we were able to provide a satisfactory analysis of its operation with the aid of Dr. Bigelow. We also made a change to the original circuit in order to improve its functionality: a capacitor was added in parallel with the diodes to allow for the circuit to function properly at higher frequencies. We are still implementing it on a breadboard.

Soldering :

Having to solder all of the parts onto the PCB had its own unique problems. Resistors and capacitors posed no problem soldering on the board but the pin dense HVP, beamformer, and the T/R switch had some bridging. For small PCB's that have only a few parts it is possible to get away with placing the solder by hand. We ordered a solder mask and used a reflow oven to assist in making sure there was less bridging for areas with more parts per area. However, even though the solder mask helped, we still had some bridging of the pins which we had to remove with a solder wick after putting the board in the oven. This had been a bit of a chronic problem with all of the boards we had soldered. The only way around this would to be getting a machine to lay the solder.

Low Noise Amplifier LMH6622:

Testing the Low Noise Amplifier (LNA) proved fruitful. We were able to get a proper output signal from testing the circuit soldered to the circuit board. However due to the resistors, our gain is improper and needs to be changed for an upcoming PCB. This part was burned shortly after testing. It was suspected that resoldering the nearby resistors to change the gain of the LNAs caused an unknown short circuit.

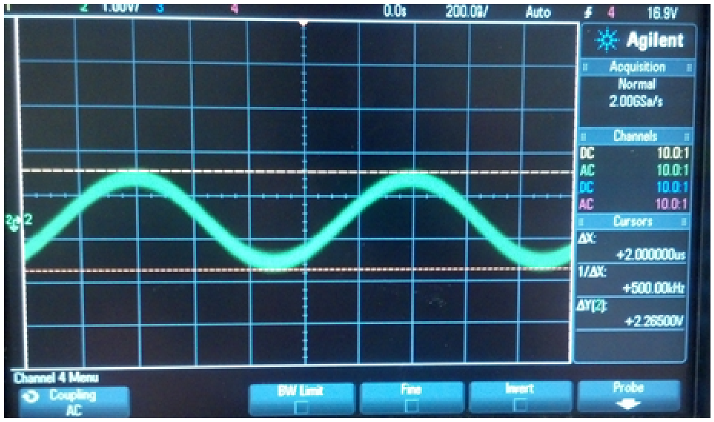

Figure 17: Output waveform of 20mv input sine wave

Afterwards we had redesigned the low noise amplifier circuit to a non-inverting 2 stage circuit to help attenuate noise. Getting a proper waveform out of the new circuit had its own problems involved with it as well. Spending some time analysing the new PCB circuit we had not be able to receive proper output for the circuit. The output we did get was a DC output of the proper voltage amplification but we did not have enough time to solve the problem.

Transmit/Receive Switch TX810:

We tested the PCB mounted part with a sine wave and were able to receive a sine wave out. It contained a small and probably negligible amount of distortion along with a small phase shift. Unfortunately, the part was burned during testing of the LNA before we could obtain a proper output signal on the first iteration of the circuit board. Upon receiving the second test board we were able to test the with a sine wave and see the input wave as expected.

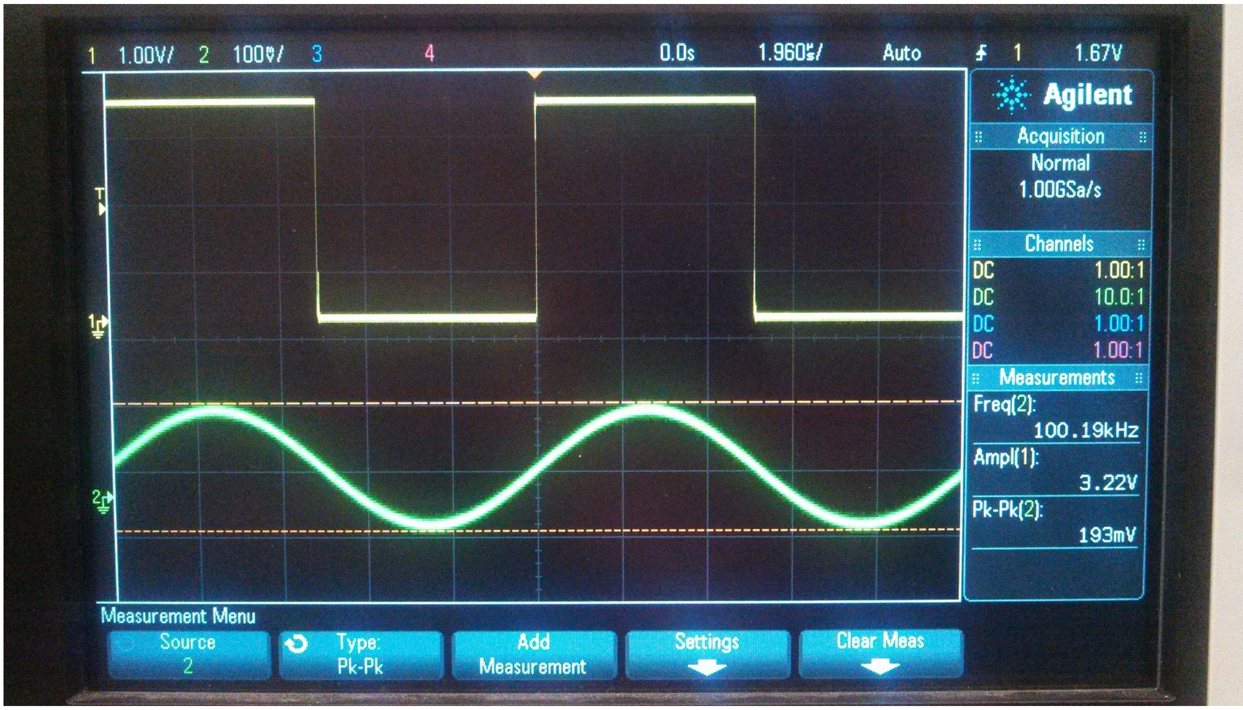

Figure 18: Output waveform of 200mv input sine wave along with trigger signal

We were able to test the circuit to make sure its protective features were operating properly too. The results showed the circuit had attenuated higher voltages to 2V as suspected.

Figure 19: Output waveform of 5v input

High Voltage Pulser LM96550:

For the LM96550 we had burned the chip and were unable to see any output. There are three suspected reasons for burning the circuit:

1. Burning of the LNA circuitry
2. Shorting the power pin to ground
3. Burning of the TX810 circuit

During our second round of testing we, had built another copy of the circuit that implements the HVP. In powering up the HVP we managed to burn the chip when reaching the 3rd stage of powering up the chip. Upon turning on the 20v for the VPP and VNN the voltage supply showed 1A of current. We suspect that the HVP turns on in a more specific method then what's explicitly written.

On the third round of testing with our final board we managed to test and burn the HVP. Having multiple group members check on the design and the data sheets to make sure the power up sequence was done properly proved to not be the problem. We guess that there might be an error in the PCBor

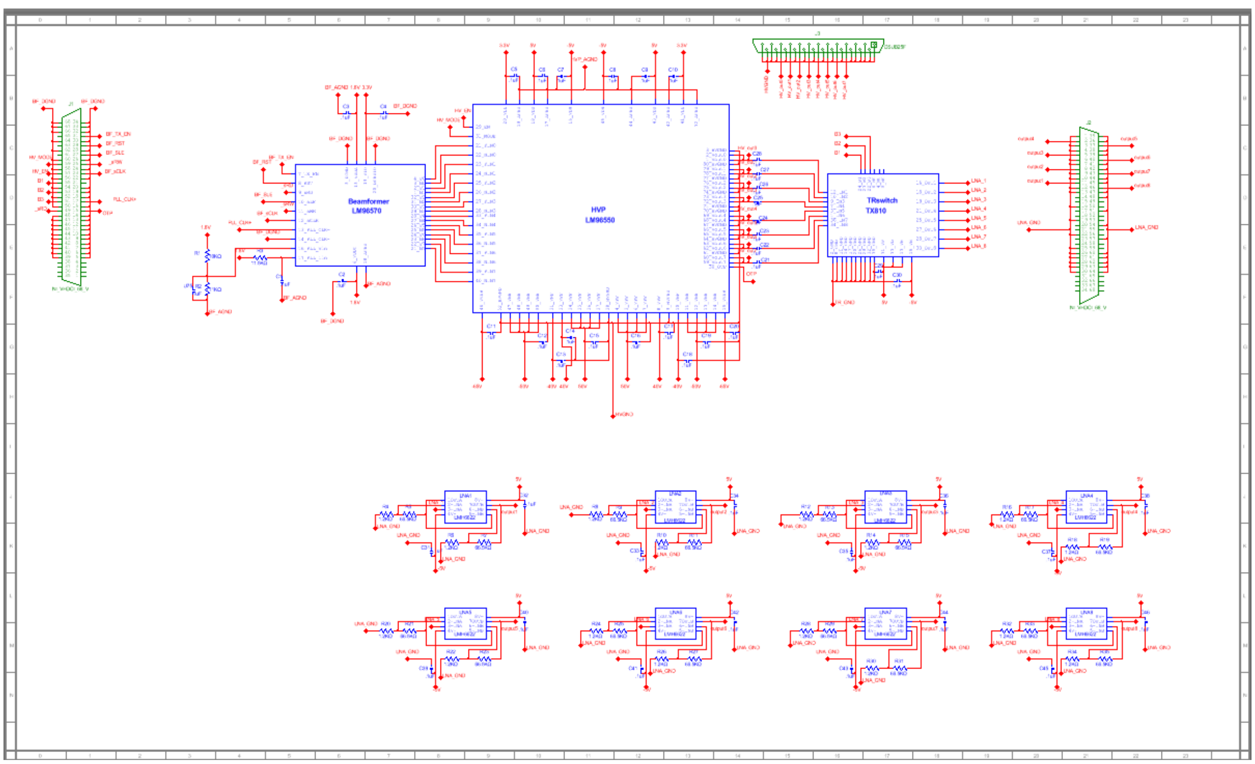

Figure 20: test board PCB in Multisim

Below is the PCB design of our final 8-channel board:

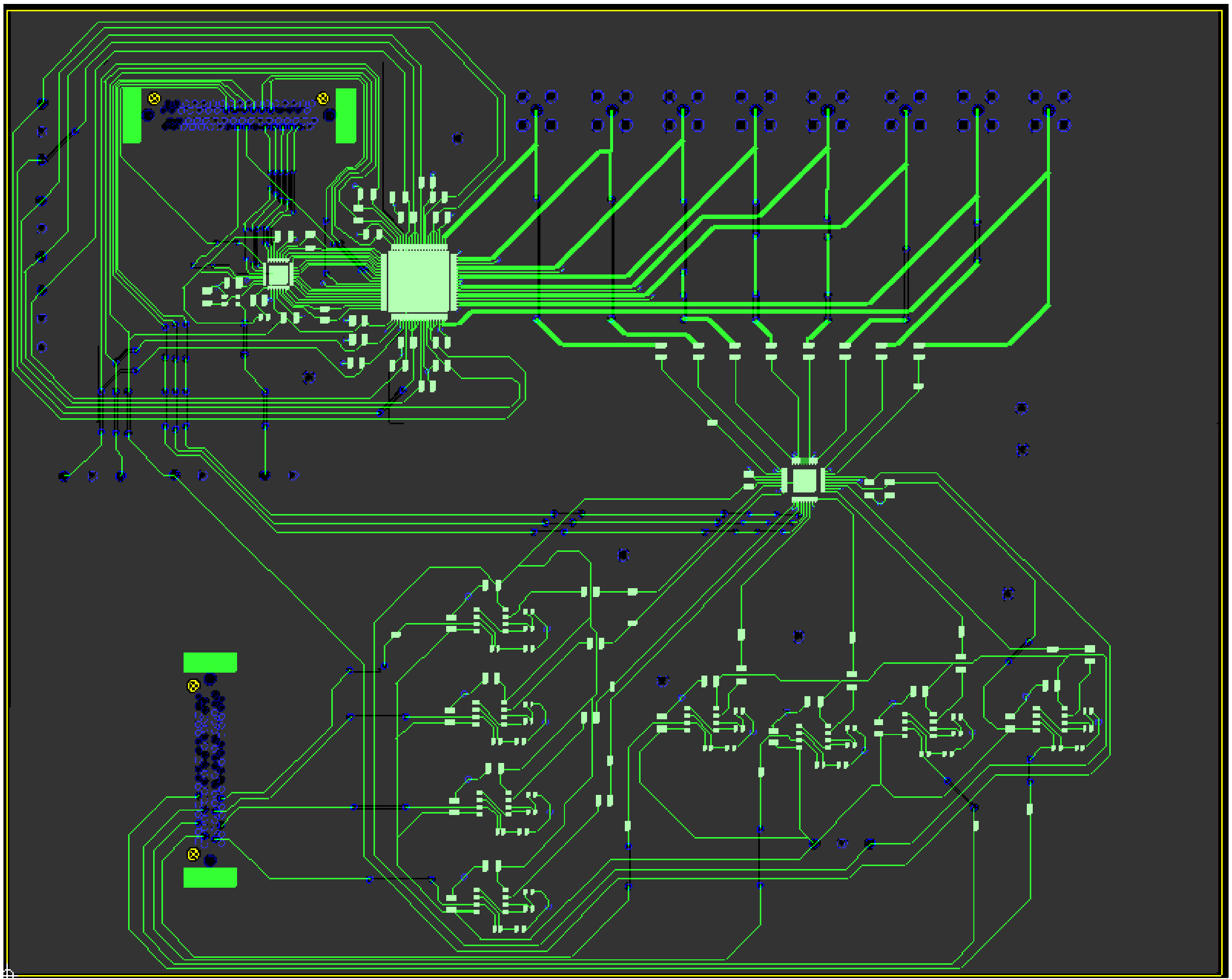

Figure 21: test board PCB in Ultiboard

Below is the I/O configuration of the test board:

Test Board Input Output:

Input (NI-5752)	Pin Name
DI 0	BF sRD
DI 1	HV_OTP
DO 0	NC
DO 1	BF_TX_EN
DO 2	NC
DO 3	BF_RST
DO 4	NC
DO 5	BF_sLE
DO 6	HV_MODE
DO 7	BF_sWR
DO 8	HV_EN
DO 9	BF_sCLK
DO 10	T/R_B1
DO 11	NC
DO 12	T/R_B2
DO 13	NC
DO 14	T/R_B3
DO 15	BF_PLL_CLK+
Output (NI-5752)	Pin Name
AI 0+	LNA4
AI 1+	LNA5
AI 2+	LNA3
AI 3+	LNA6
AI 4+	LNA2
AI 5+	LNA7
AI 6+	LNA1
AI 7+	LNA8
AI 8+	NC
AI 9+	NC
AI 10+	NC
AI 11+	NC

AI 12+	NC
AI 13+	NC
AI 14+	NC
AI 15+	NC

Table 8

Standards

Circuit Design:

We performed all circuit design and simulation in National Instruments Multisim.

PCB Design:

We performed all PCB design in National Instruments Ultiboard.

Budget

This semester we had a senior design budget of $1000. The majority of our budget was used to purchase the parts needed for our 8-channel test board. Below is a breakdown of how our money was spent:

Spring Semester 2013					
date purchased	part	part number	quanity	unit price	extended price
4/8/2013	10kohm resistor	P10KGCT-ND	10	0.1	1
4/8/2013	11kohm resistor	P11KGCT-ND	10	0.1	1
4/8/2013	11.5kohm resistor	P11.5KHCT-ND	10	0.1	1
4/8/2013	sma connector	ACX1231-ND	15	3.87	58.05
4/8/2013	High Voltage Pulser	LM96550	5	30.25	151.25
4/8/2013	Beamformer	LM96570SQX/NOPB	5	9.91	49.55
4/12/2013	female connector to transducer	1003-1647-ND	1	265.5	265.5
4/12/2013	VHDCI Connector, 68-Pin, Vertical, PWB Through Hole Mount	780389-01	2	21	42
4/12/2013	1.2kohm resistor	P1.2KGCT-ND	50	0.0092	0.46
4/12/2013	66.5kohm resistor	P66.5KHCT-ND	50	0.0138	0.69
4/18/2013	PCB		1	33	33
4/18/2013	mask		1	130	130
4/26/2013	10kohm resistor	P10KGCT-ND	40	0.1	4
4/26/2013	15kohm resistor	P15KGCT-ND	20	0.1	2
4/26/2013	20kohm resistor	P20KGCT-ND	20	0.1	2
4/26/2013	30kohm resistor	P75KGCT-ND	30	0.1	3
4/26/2013	100kohm resistor	P100KGCT-ND	10	0.1	1
4/26/2013	150kohm resistor	P150KGCT-ND	30	0.1	3
4/26/2013	200kohm resistor	P200KGCT-ND	10	0.1	1
	total				749.5
Fall Semester 2013					
date purchased	part	part number	quanity	unit price	extended price
10/31/2013	low noise op amps	LMH6622MA/NOPB-ND	20	3.195	63.9
11/11/2013	PCB		2	33	66
11/11/2013	mask		1	130	130
11/21/2013	connectors	A34097-ND	6	4.23	25.38
11/21/2013	cables	AE9863-ND	3	5.83	17.49
	total				302.77
	total both semesters				1052.27

Figure 22: budget for spring and fall semester

Future Work

Going forward, there are several things that need to be designed and modified.

1. Connection board

   We were not able to implement the connection board to the transducer this semester due to time and budget constraints. Future groups will need to design two 6 layer boards to be able to connect to the two 260 pin transducer connectors.

2. Programming of NI PXI system

   We have yet to receive the NI PXI system but upon receiving it, it will need to be programmed. It will need to send the control signal to the beamformer and to analyze the set of data received to produce an image.

3. Integrated Power Solution
   Currently we require multiple power supplies and cables to power the system. A single power supply would make operation of the system easier in the future.

Conclusion

Throughout the last two semesters our group members have learned a great deal while workingon this project. Using resources provided by the university we were able to gain experience working as a team to develop a product from start to finish. We gained skills in PCB design, circuit design and simulation, testing, product research, budgeting, and time management.

Operation Manual:

The LM96550 datasheets provides a specific power up and power down sequence that needs to be followed in order to safely power the device. The sequence should also be followed when testing the LM96570 device as they share a supply.This sequence is detailed below in the Power-Up and Power Down Sequences section.

When sending pulses from the High Voltage Pulser it is also necessary to power up the TX810 with the 5 V and -5 V supply, so that high voltage pulses do not damage the LNAs. If testing just the receive circuitry (amplifier and TX810 IC) it is not necessary to power up the beamformer and high voltage pulser.

Power-up and Power-down Sequences

VSUB must always be the most negative supply, i.e., it must be equal to or more negative than the most negative supply, VNN or VDN. VPF ≥ VPP −14V AND VNF = ≤ VNN +14V at all times.

Power UP Sequence:

1. Turn ON VSUB, hold EN pin LO
2. Turn ON VLL
3. Turn ON VDD, VDN, VPP, VPF (VPP-10V), VNN, and VNF (VPP-10V)

Power DOWN Sequence:

1. Turn OFF VDD, VDN, VPP, VPF, VNN and VNF
2. Turn OFF VLL
3. Turn OFF VSU