

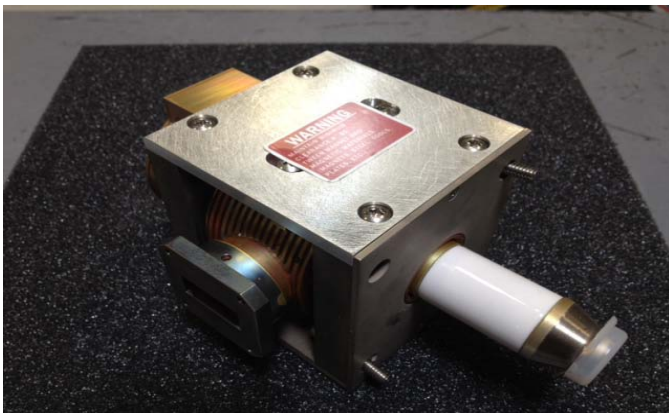
# Magnetron Automatic Frequency Control System

John C. Turner

**Abstract** — This paper is a report on the purpose of my senior design project and its design and implementation. I will begin with a brief overview of the system this project will be integrated into and why this design is necessary. I will also detail the how the circuit was designed along with its corresponding software and firmware and give an overview of how it all fits together to accomplish the design purpose.

## I. INTRODUCTION

THIS project entails a control system for the automatic frequency adjustment of a magnetron running in a high energy x-ray system. This system shall be referred to as the automatic frequency control, or AFC, system. Here are a couple of pictures of an x-band magnetron whose peak RF output is about 350kW and can run at a 0.1% duty cycle:



The tuning shaft can be seen in the following picture:



## II. SYSTEM OVERVIEW

The typical magnetron-based high-energy x-ray system consists of three major components: the modulator, the RF unit (RFU), and the x-ray head. The modulator generally contains the power distribution and control system and is responsible for generating high voltage (typically 20-30kV) pulses to send to the RF unit. The RF unit contains a step up transformer that steps up the pulse voltage to an appropriate level for the RF source, or magnetron, to be able to generate RF pulses (250kW to 2.5MW). These RF pulses are then transmitted via waveguide to the x-ray head. In the x-ray head the RF is coupled into a linear electron accelerator. The accelerator also has an electron gun, which receives a high voltage pulse at the same time the RF pulse is applied. This gun injects electrons into the accelerator structure, which are accelerated to near the speed of light by the standing RF wave set up in the resonant cavities of the accelerator. At the end of the accelerator these electrons collide with a target, which in turn emits photons in the form of x-rays.

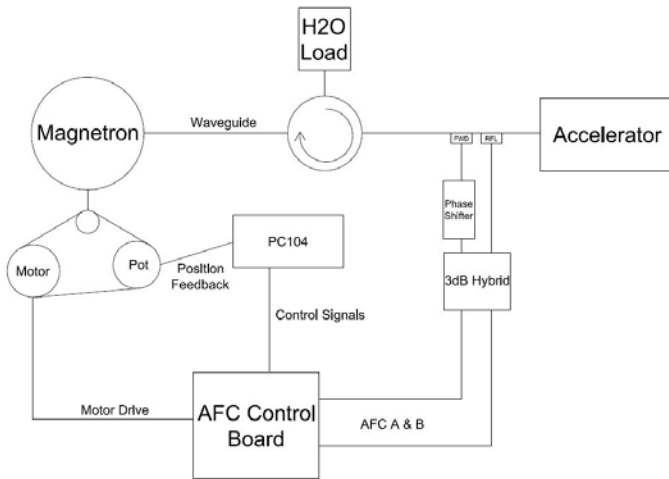
Recently, x-ray machines of a different topology (monoblock) have been developed in which all three of the above mentioned components (modulator, RFU, and x-ray head) have been integrated into a single chassis with a small footprint for smaller mobile applications. Given this new dynamic there is no longer a section of the machine on which to mount components that need to be accessed by factory technicians and field service engineers while the machine is producing radiation. On previous designs such components would typically be mounted in the modulator frame, which would be located in a remote location from the x-ray head allowing easy access to those components during a ‘beam-on’ condition. The AFC PCB is one of those components, which requires a high level of calibration specific to each individual machine, which calibration must be performed while the machine is beamed on.

## III. AFC SUBSYSTEM OVERVIEW

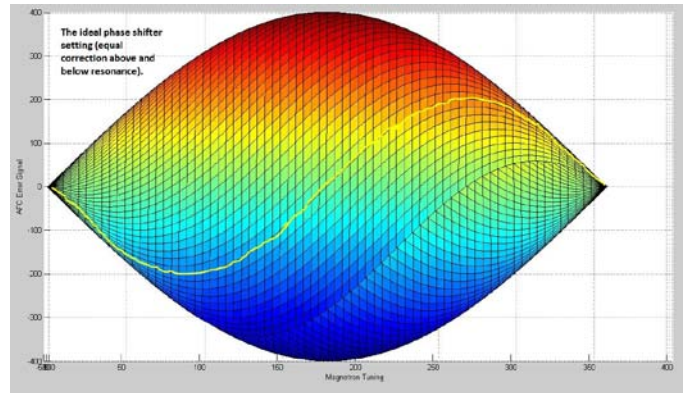
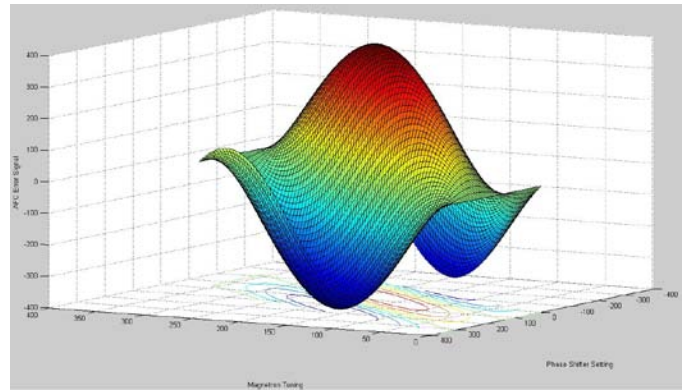
One of the most vital pieces to reliable performance of the x-ray machine is the Automatic Frequency Control (AFC) system. In order for the electrons to be properly accelerated, there must be a standing wave set up in the resonant cavities of the accelerator structure. In order for the RF pulse to be

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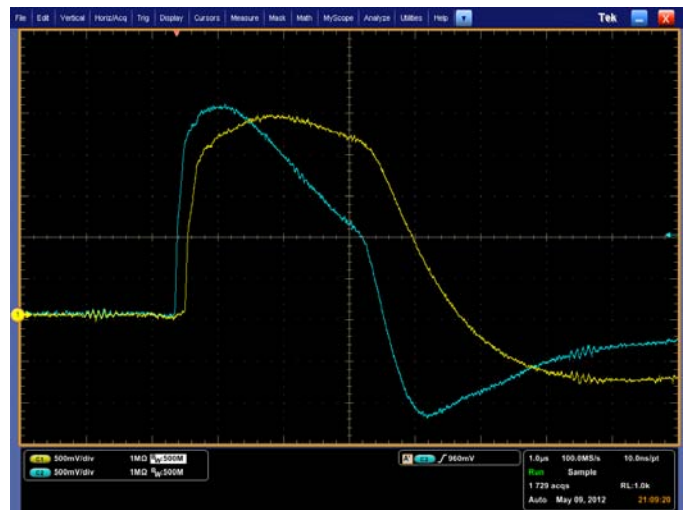
effectively coupled into those cavities, it must be EXACTLY the right frequency (the resonant frequency of those cavities). The RF frequency can be manually adjusted at the magnetron by physically turning a tuning shaft. The challenge is that the RF frequency must be dynamically tuned as the machine operates. Once the machine is beamed on, a lot of heat is generated, and a good portion of this is dissipated in the magnetron and the accelerator. As this heat causes the cavities in the magnetron and the accelerator to expand, their resonant frequency changes, so the magnetron must be continually tuned to ensure that it is continuously transmitting the resonant frequency of the accelerator. A block diagram of an existing system can be seen below (the AFC Control Board is the piece that needs to be manually calibrated by a technician):



The feedback mechanism for the control system to know how to tune the magnetron starts as RF signals taken from directional couplers from the waveguide, one tuned to pick up forward (FWD) power, or incident wave, and one tuned to pick up reflected (RFL) power, or the wave reflected from the accelerator. The FWD signal is then passed through a phase shifter after which it, along with the RFL signal are fed into a 3dB quadrature hybrid. The hybrid basically takes two signals in and gives two signals out, and the amplitude relationship of the output signals is relative to the phase relationship of the input signals. Also, the RF signals are passed through video diodes at the output of the hybrid, which rectifies the RF and forms an envelope the same shape as the RF pulse. These two output signals used in the control system are known as AFCA and AFCB. Since the phase of the RFL signal changes w/respect to the FWD signal as the degree of mismatch changes at the accelerator, this information can be used to know which direction to tune the magnetron to correct the mismatch and tune back to resonance. The difference between these two signals is what is used as the error signal. The purpose of the phase shifter is to set up the initial phase relationship between FWD and RFL signals to allow for equal amounts of correction on either side of resonance. This relationship can be seen below:



The following oscilloscope shot shows what the AFCA and AFCB signals look like coming out of the 3dB quadrature hybrid:



## IV. EXISTING ISSUES

### A. New Location

As mentioned above, the existing system was designed to be calibrated by a test technician by tweaking a series of trim pots located on the control card. In order for AFC to be calibrated, the machine must be beamed on. On most machines this is not a problem because this card is located in the modulator. The modulator is a cabinet that sits outside of the radiation area,

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meaning that the technician has full access to it during a beam on condition. In a monoblock machine, all components, including the modulator, have been incorporated into a single chassis. This means that the AFC control board is not accessible to the technician while beamed on. Currently in the factory this is overcome by stringing a long cable with extension adapter boxes on either end to a bench in the operator's area, allowing the trim pots to be adjusted remotely. In some cases the feedback signals and/or the motor drive signals become very distorted on this cable, making calibration very difficult and giving rise to the possibility that the board may not behave the same way when placed back in the machine. An even bigger issue that has not been observed yet as this is still a new product, is that inevitably a field service team will need to set up AFC in the field, and should not have to lug around an extension cable and boxes to do so. The ideal solution would be to have an AFC system that can be calibrated via a remotely accessed GUI running on the PC104 (the control system computer) that is linked to the AFC control board.

### B. DC Motor Issues

The current system uses a 12 V DC motor to turn the magnetron tuning shaft. The motor is coupled to the shaft with a plastic chain, which also links it to a feedback potentiometer (so the control system knows where the magnetron tuning shaft is at in order to prevent it from driving past the end stops). The majority of the time this works OK but there are some issues. Currently this motor is driven with a pulse width modulated H bridge and there exists a region where the error signal generated by the feedback signals is large enough to cause the controller to try to drive the motor, but the resulting duty cycle is not high enough to drive the rotor of the motor to the next pole, so until the error signal grows large enough the motor just sits there and 'twitches'. This region varies from machine to machine as well depending on the tension of the belt. The other issue is that there is some inherent slop in the belt drive system, which hasn't been a major issue on the s-band (3 GHz) system it was adapted from, but on the x-band (9.3 GHz) system it has been found that effective tuning requires a much higher level of precision and sensitivity.

### C. Control Signal Integrity

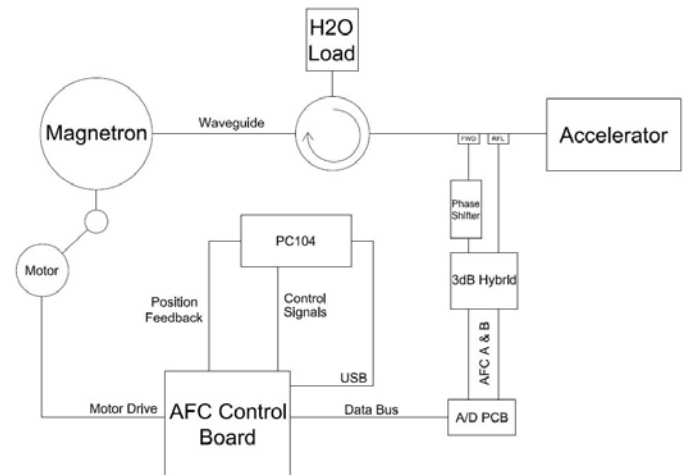
The AFC signals generated in the 3dB quadrature hybrid must necessarily run from the front of the machine to the back of the machine where the control system is located. Given this cable run, and even more so, the connection points the signal must pass through, there is a lot of opportunity for those signals to pick up a lot of noise due to the extremely high levels of EMI generated by the pulsed power (up to 1MW peak at a duty cycle of up to 0.0015). Clean AFC signals are crucial for effective control of the system.

## V. SOLUTIONS FOR EXISTING ISSUES

In order to solve the calibration issue, I am implementing a control system whose calibration takes place via a GUI running on the onboard PC104, which is accessed remotely from a remote desktop application and requires nothing more than an Ethernet cable which is already installed at most customer sites. This GUI will interface with the new AFC control board via USB.

To solve the DC motor issue, I will be replacing it with a stepper motor to eliminate the guesswork caused by the existing motor controller and corresponding H-bridge. The stepper motor will be directly coupled to the magnetron tuning shaft and motor positioning will be determined by a pulse counting scheme rather than feedback from a potentiometer. The reason it is necessary to know where the motor is at is because it must return to the same position every time the machine is 'beamed off' in order for the next 'beam on' to start producing x-rays immediately rather than having the AFC to hunt for the resonant point for a few seconds.

In order to guarantee clean AFC signals, I have designed a data acquisition (DAQ) board that digitizes the signals as close to the source as possible and transmits them to the control board via I2C bus using an LVDS signal transmitted over a shielded Ethernet cable for noise immunity. The new block diagram can be seen below:



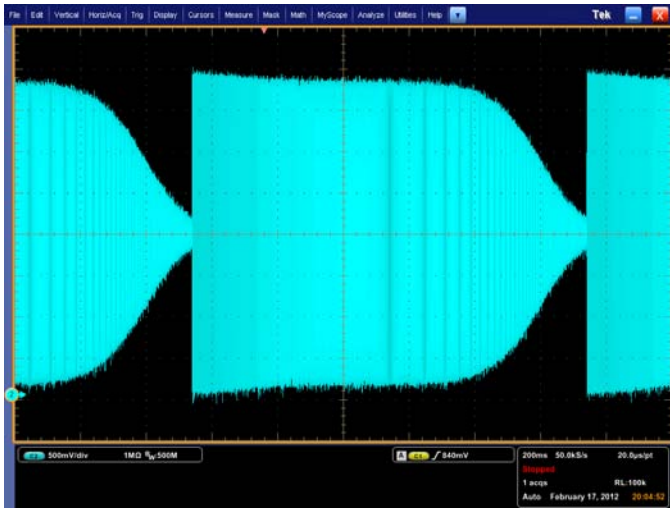
## VI. DATA ACQUISITION (DAQ) PCB

The design of the DAQ board is fairly straightforward. The AFCA and AFCB signals connect to the board via SMA connectors and go to a 1k ohm input buffer, after which they go through an active low pass filter with a 1.5MHz passband and a stopband (-45dB) at 2MHz) to filter off any noise that may have been coupled onto the signals between the waveguide and the board. The op amp chosen for this circuit is the OP467 from Analog Devices and was chosen for its high GBWP and very fast slew rate in order to not distort the relatively fast pulsed signals. Here is an oscilloscope shot that

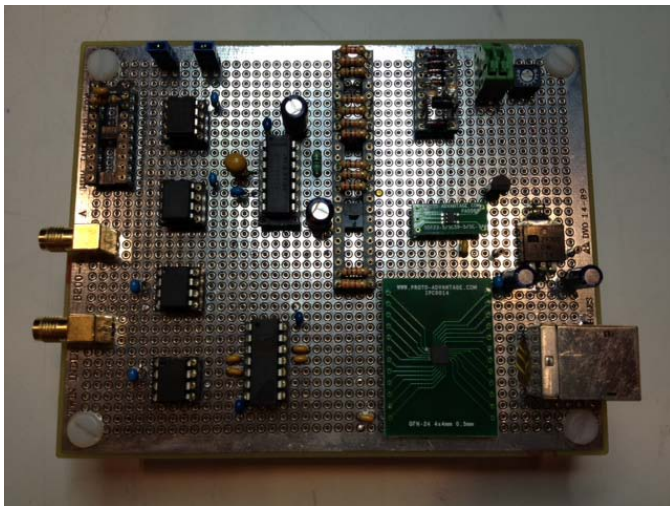


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shows a 1kHz to 2.5MHz logarithmic sweep of the filter showing its response:

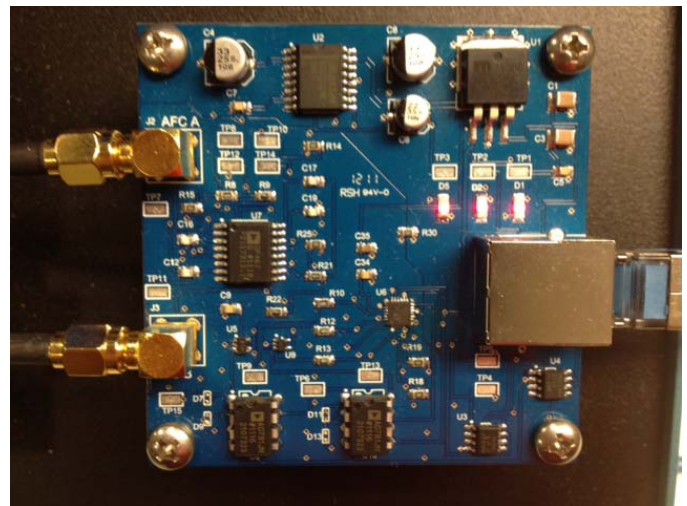


These two signals are then fed into sample and hold chips. Since this is a pulsed signal it is necessary to sample it during the pulse and then feed the held value into the A/D converter so the rest of the control can be handled asynchronously from the pulse timing of the machine. The LTC2309 from Linear Technologies is the A/D chip that was chosen for the board. It was chosen mainly for its high speed throughput (14000 samples/second), but also because it has multiple input channels, a wide rail to rail input range, 12 bit resolution and an I2C serial output interface. The output is then fed into an I2C to LVDS line driver transceiver and transmitted to the control PCB over one of the twisted pairs of a shielded Ethernet cable. This board also gets its power (15V) via two pairs of this cable so that a separate power cable does not have to be routed to the board. The other twisted pair in the cable transmits the gate signal (RS422 protocol) for the sample and hold chips. A schematic of this board is attached at the end of the report. Here is a picture of the prototype that was built:



When the final layout of the board was done, careful

consideration was taken to isolate the grounds of the digital circuitry from the grounds of the analog circuitry. Analog components were placed on one side of the board and digital components were placed on the other side of the board, with the A/D converter placed in the middle along with a 0 ohm resistor tying the two grounds together at a single point. 0 ohm resistors were also used to connect analog and digital grounds to the chassis ground used for the mounting holes. Resistors were chosen in order to be able to remove them if necessary to improve the grounding scheme after board fabrication. Care was also taken to place extra footprints around the op amps to be able to reconfigure the filter as an inverting filter if necessary by selectively populating the appropriate components without having to redesign the board. Also included on the final layout was a precision 5V reference for the A/D converter and a -12V inverting regulator to provide the negative voltage rail for the op amps and the sample and hold chip. Since there were spare channels available on the A/D converter, a temperature sensor was also added to the board to provide temperature information from the part of the machine this board gets mounted in. LED's were also located on the board to indicate that all DC voltages were working and test points were strategically located around the circuit to allow for a high level of testability of the final board. Here is a picture of the final fabricated PCB:



## VII. AFC CONTROL PCB

The control board is a little more complex than the DAQ board. At the heart of the board is a PIC 18F4550 microcontroller which is essentially programmed with the control system. There were many reasons the PIC was selected for the system. The MPLAB integrated development environment from Microchip is free and comes equipped with many features that aid in development, including some very useful debugging features. There are a couple of free C compilers that can be used with MPLAB as well and the support forums are extremely helpful. The C18 compiler used for this project also has a lot of free libraries that ease code development. The 18F4550 also has lots of built in features that were needed for the project. These included onboard

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USB module, A/D converters, EUSART with I2C function, timers, internal and external interrupts, internal EEPROM, lots of digital I/O, in-circuit serial programming and a highly configurable internal oscillator to clock the CPU.

Most everything else on the control board revolves around the microcontroller. One of the other main components is the stepper motor controller, the A4988 from Allegro Microsystems. This chip greatly simplifies the driving of the stepper motor that is used to turn the tuning shaft on the magnetron. It simply takes a few discrete inputs from the microcontroller, such as motor direction, output enable, step size (full step through 1/16<sup>th</sup> step) and motor step (motor steps when it sees a rising edge). The chip also has a current limiting feature that can be used to limit the torque of the motor to make sure it doesn't exceed the magnetron tuner's torque specification when it reaches the end of its travel. The chip is powered by 5V but drives the motor windings with 24V.

The microcontroller also interfaces with the discrete control signals from the PC104. The following 6 signals are fed to the AFC control board:

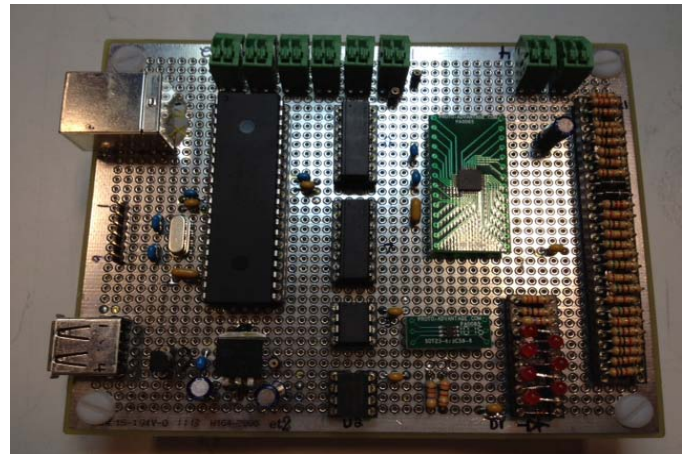
- System Trigger – used to generate the gate signal for the sample/hold chips
- Beam ON/OFF – indicates whether or not the machine is beamed on
- Manual/AFC mode – indicates whether an operator has requested manual control of the magnetron tuner
- Motor UP – drive motor up, used only in manual mode
- Motor DOWN – drive motor down, used only in manual mode
- HI/LOW mode select – currently unused but may be implemented on multi-energy x-ray machines

These signals are at a 24V level coming onto the board, so they are fed through optocouplers to convert them to 5V levels and provide a level of isolation. The exception is the system trigger which is level shifted with a FET because the optocoupler is not quite fast enough. There is also a temperature sensor on the board which is fed into one of the A/D converters on the PIC to provide temperature information for the location of the machine that the control board is mounted in.

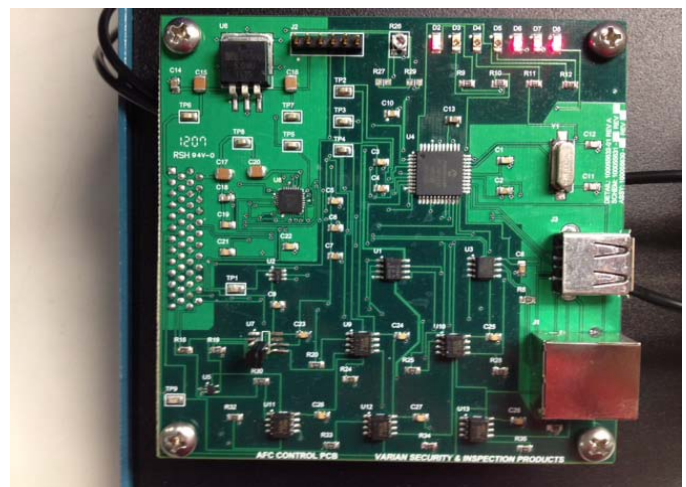
The PIC, upon seeing the rising edge of the incoming system trigger, generates a pulse that is the gate for the Sample and Hold circuit on the DAQ PCB. Prior to being sent to the DAQ PCB this 5V signal is fed through a MAX1487 chip to convert it to RS422 levels for noise immunity as it is to be transmitted through a very high EMI environment. Similarly, the I2C clock and data signals are fed through a P82B96 chip from NXP semiconductor, which is made to convert I2C 5V signals

to low voltage differential signals (LVDS) in order to transmit them over long distances or through noisy environments.

Since this AFC system is meant to replace an existing system which provides magnetron tuner position feedback to the PC104 with a DC voltage from a potentiometer, a D to A converter has also been incorporated onto the board to provide this feedback to the PC104. The analog output of the D/A scales to the position of the motor by relating it to the step count. The D/A is programmed serially from the I2C interface with the PIC. There are also 3 LED's on the board that indicate that the 24V, 15V and 5V supplies are on as well as 4 more LED's connected to output pins on the PIC to assist with debugging and provide visual indications of system status. Finally there is an ICSP (in circuit serial programming) header on the board to be able to program the PIC microcontroller. Here is a picture of the prototype board that was used for development:



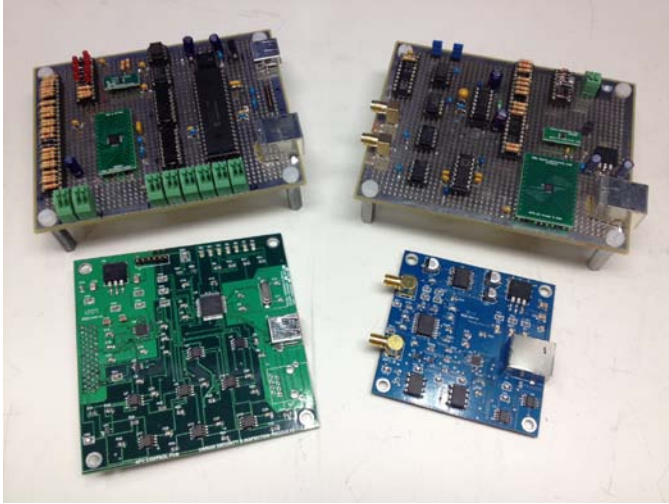
After the prototype was taken to a point where the hardware was working I did the layout of the final board in Altium. The DIP packages were converted to surface mount packages and special care was given to the routing of the differential pairs as well as the trace widths for the high current traces. Other than that the layout was fairly straightforward. Here is a picture of the final fabricated PCB:





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The following picture shows the prototype boards next to their corresponding final PCB assemblies:



### VIII. FIRMWARE

The firmware for the PIC microcontroller was written mainly in C using the free C18 compiler from Microchip. There is a lot going on in the microcontroller, here is a high level overview of most of what is happening.

Microchip provides USB libraries that can be used in projects with their microcontrollers that have the built in USB communication module. It takes some effort to learn how to use them, but once properly configured they make code development easier and allow the product to comply with the official USB standards.

The first thing that happens upon power on is microcontroller initialization. The PIC is driven with a 20MHz external crystal oscillator, which is then divided down to 4MHz internally, fed into a 96MHz PLL and then divided by 2 to clock both the CPU and the USB module at 48MHz. The oscillator is configured in the chip's configuration bits along with a few other settings in order for it to be able to properly power up and begin executing instructions. Once running, the PIC executes the initialization function to initialize the peripherals to be used. These include the digital I/O, analog inputs for the A/D module, I2C port, timers, interrupts, and USB module. It also reads the calibration constants out of the EEPROM and assigns them to the appropriate variables.

After initialization and before entering into the main processing loop, the PIC zeros the stepper motor so that its position can be tracked during operation. The motor is driven 25 turns in one direction to ensure that it is all the way to one end of the magnetron's tunable range (the magnetron has a full range of 24 turns). The motor is selected so that its max torque does not exceed the torque specification of the magnetron's tuning shaft so as not to cause damage upon

reaching the end of travel. In order to not stress the shaft in one direction, this initial direction the motor is driven changes each time the system is powered on (the direction is tracked in EEPROM). After driving 25 turns the motor then switches direction and backs up 12 turns to put it in the center of the magnetron's tunable range and sets a counter to 0. From this point on every step of the motor is tracked. The main reason for this is that the magnetron tuner must be in the same place every time the machine is 'beamed on' in order to start immediately producing x-rays rather than having to hunt for the resonant point for a few seconds. After the motor is zeroed it then goes to that 'cold start point' which is defined by a technician during calibration.

After the motor has been zeroed the program enters into its main execution loop. The first thing that happens is to check the status of some of the control signals from the x-ray machine as well as flags indicating the status of the radio buttons on the GUI. This determines which of the following six modes to go into: GUI Manual, GUI Calibration, Beam On Auto, Beam On Manual, Beam Off Auto, and Beam Off Manual. Most of the time the machine will be in Auto mode, meaning that it is automatically tuning the magnetron. When in Beam On Auto mode the PIC continuously performs D to A conversions on the output of the sample and hold chips and temperature sensors on both boards. It then generates an error signal by taking the difference of the two AFC signals. This error is then compared to a target that is calculated during the calibration sequence. If the difference between the error and target is big enough the motor driver chip is enabled and the motor is driven in the appropriate direction at the appropriate speed (determined by the sign and magnitude of the difference between the error and target) until the system is back on resonance. When enabled, the motor is stepped at the same interval which is determined by the value loaded into a timer. When the timer counts down to zero an interrupt is generated, at which point the motor is stepped and the timer is restarted. One other interrupt is used during program execution as well when the microcontroller sees the rising edge of the x-ray machine trigger. Upon seeing this edge the PIC executes a delay and then generates a pulse of a certain width which is the gate pulse used by the sample and hold chips on the DAQ. The delay and width of this pulse must be precisely timed to sync up with the AFCA and AFCB signals, which are only about 3-4  $\mu$ s long and happen at a rate of anywhere from 50 to 400 times/second (these pulses occur about 4 $\mu$ s after the rising edge of the machine trigger). This interrupt had to be written in assembly code to be able to execute quickly enough to catch those signals. The delay and pulse width are programmable via the GUI and the programmed values are stored in EEPROM. When the machine is beamed off and still in auto mode it simply turns the motor back to the cold start point (defined in calibration and stored in EEPROM) and waits to be beamed on again. The following scope shot shows the two AFC signals (blue and pink) along with the sampling pulse (yellow) and the corresponding output (green) of one of the sample and hold chips (sampling the pink signal):



When the machine is in any of the manual modes it simply stops auto tuning and waits for user input to determine when to drive the motor. In GUI manual mode it looks for the user to click the UP or DOWN button and drives in that direction. In either of the other manual modes it looks for input from the discrete UP or DOWN signals from the x-ray machine control system (which are asserted by the user from the main control system interface).

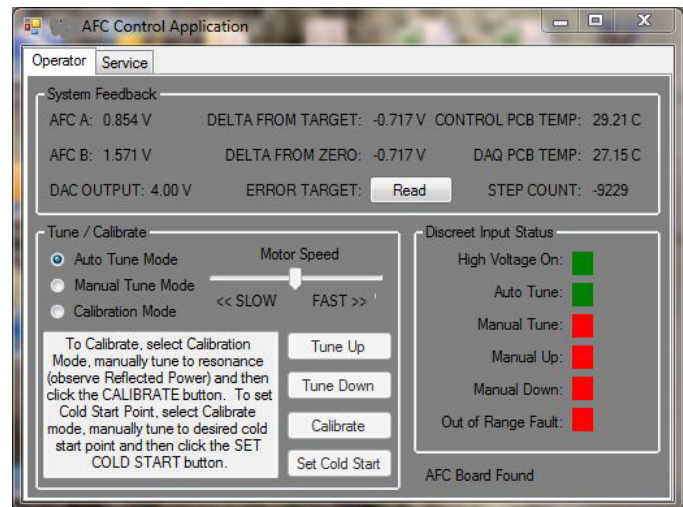
When the system requests calibration mode, the microcontroller essentially goes into GUI manual mode but also opens up to two further commands from the user. One of these commands is the 'calibrate' command. To calibrate the system, the user simply manually tunes the magnetron (using the UP and DOWN buttons on the GUI) until the machine is on resonance (the operator can make this determination very easily by monitoring a couple of signals, but this discussion is beyond the scope of this paper) and clicks the Calibrate button. The microcontroller takes the difference between the AFCA and AFCB signals at that instance and sets that as the target discussed above. The target is then written into the EEPROM so that it is not lost when the machine is powered off. The other command that the user can send in calibration mode is the 'set cold start' command. As previously described, the magnetron tuner must be in the same position every time the machine beams on so that it immediately produces x-rays instead of hunting for resonance for a few seconds before producing x-rays. Again, the user simply manually tunes to the desired position and clicks the Set Cold Start button. The microcontroller then stores the current position of the motor in EEPROM. Then whenever the machine is beamed off and in auto mode it goes to that point so is in the correct position for the next time the machine is beamed on.

## IX. CONTROL/CALIBRATION APPLICATION

The GUI for the user, or control application, was written in C# using Microsoft Visual C# 2010 Express. The AFC control

PCB connects to the PC104 computer via USB, where it communicates with the control application. It should be noted that the AFC control system can function independently of the control application and the USB link does not have to be active for it to function. In all reality the control application will likely only be used during calibration to set up the board and may never be used again during the life of the system.

In addition to providing the calibration interface as described above, the GUI also provides a lot of meaningful feedback from the control system to a technician or user. It displays the temperature at each of the PCB's, the amplitude of each of the AFC signals, the difference between the two signals (the error signal), the difference between the error signal and the target, and the motor position in terms of step count. It also provides visual indicators of the status of all of the discrete input signals. On the second tab it also provides an area to program the delay and width of the sample pulse as described above. And finally there is an area of the GUI where the calibration is performed as well as where the manual tuning is performed. This section includes a slider bar where the speed of the motor can be adjusted for the manual tuning function. The following is a picture of the control application:



## X. SIMULATION BOX

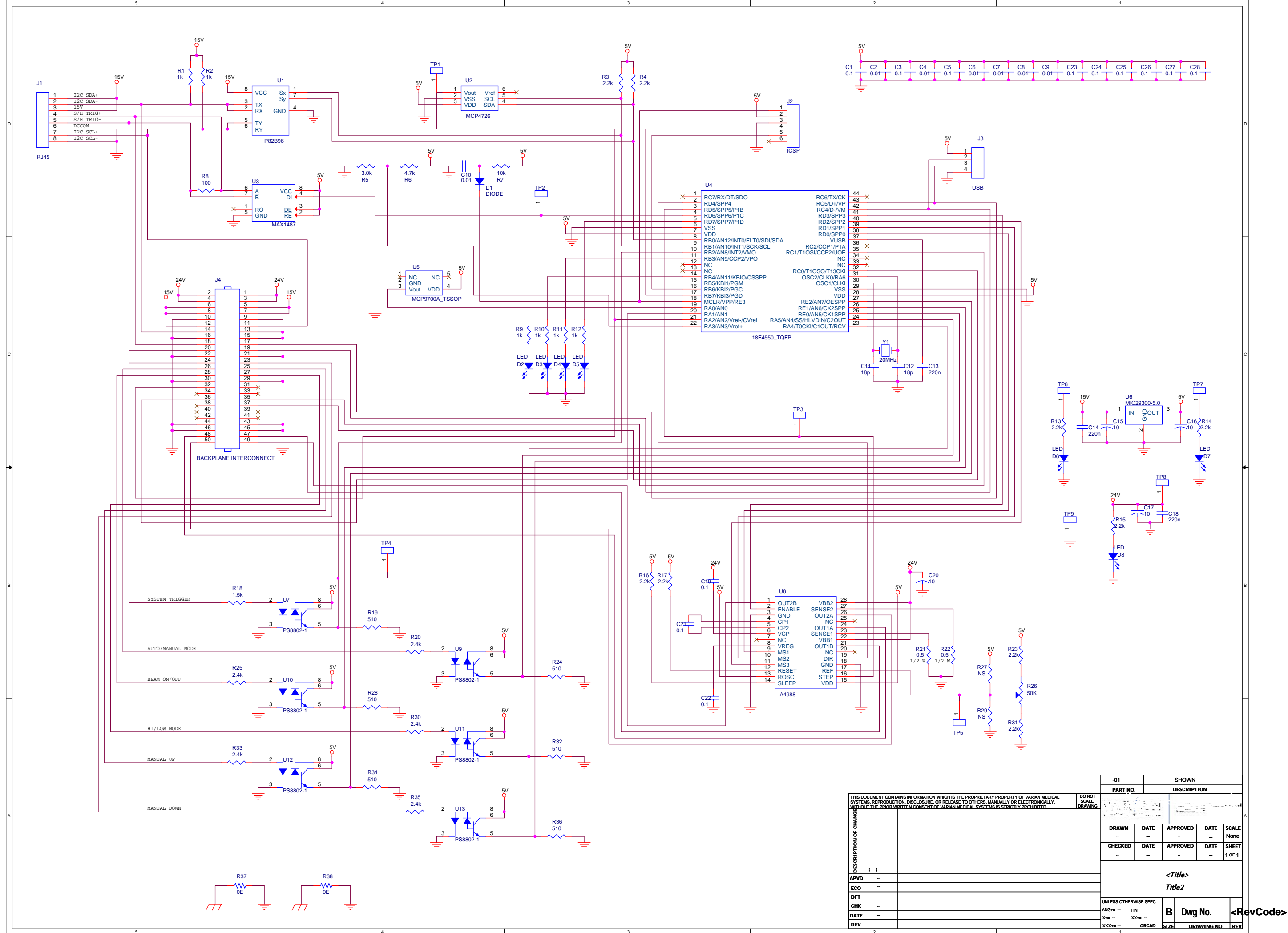
Due to the fact that an x-ray machine was not available to aid in the development of the AFC control system, I designed and built a test box that would simulate the x-ray machine. The box runs off of 120Vac and has a series of switches and knobs to toggle/adjust the discrete 24V input signals as well as the pulsed AFCA and AFCB signals with the appropriate timing as would be seen in the x-ray machine. Also, given that the control board is intended to be plugged onto a backplane PCB, through which all signals (including the USB and LVDS signals) will be routed to their appropriate interconnects, those corresponding connectors were built into the simulation box. Pictures of the box are shown here:



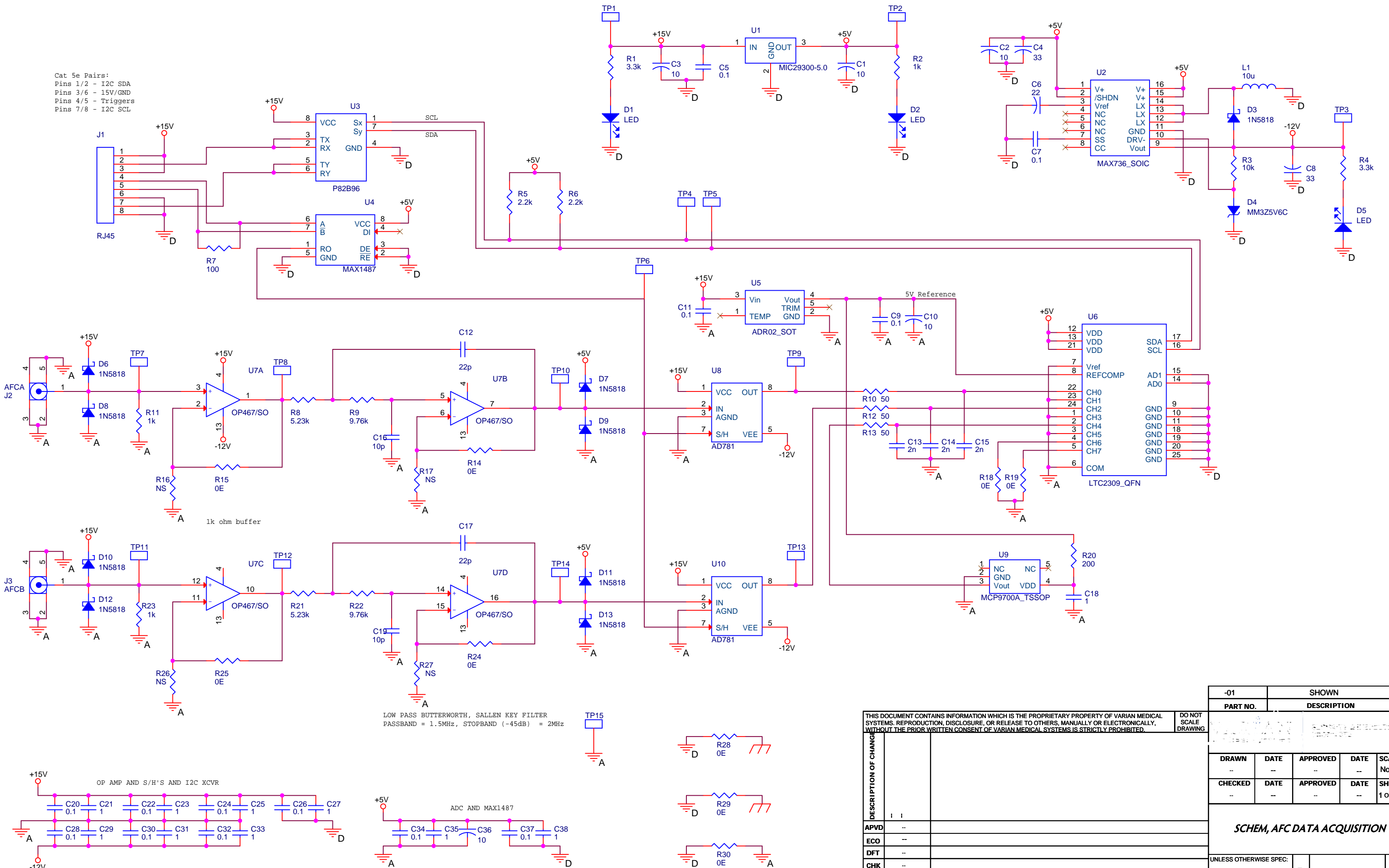
## XI. FINAL COMMENTS

This project was a challenge to work on but provided many opportunities to learn about different technologies. From hardware development to USB and I2C buses to PCB design to firmware development and GUI development, there were many facets of this design that provided their own challenges. Despite these challenges I was able to get the project completed to a point where it can be demonstrated and is proven to be working on the simulation box. Prior to being released in an actual x-ray machine, however, there is some additional work to be done. The stepper motor used in development was a 7.5 degree/step motor. I would likely choose a 1.8 degree/step motor for the target application to provide higher resolution to the tuner. Also the control loop to drive the motor is somewhat crude as currently implemented and I am currently working on implementing a PID loop to be able to more appropriately tune the control loop to match the response of the system. Other than that I have a very high level of confidence that this system is ready to be implemented in a high energy x-ray machine.







Cat 5e Pairs:  
Pins 1/2 - I2C SDA  
Pins 3/6 - 15V/GND  
Pins 4/5 - Triggers  
Pins 7/8 - I2C SCL



LOW PASS BUTTERWORTH, SALLEN KEY FILTER  
PASSBAND = 1.5MHz, STOPBAND (-45dB) = 2MHz

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