CERN Summer Student Project

Fibre Optic Notch Filter
For The Antiproton Decelerator
Stochastic Cooling System

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1 ABSTRACT

The duration of the project was 8 weeks (5 of which included lectures). The project scope included reverse engineering, upgrading, and recovering the operational conditions of an existing fibre optic notch filter. Once operational, tests were to be preformed to confirm the performance of the temperature stabilisation. The end goal is to use said notch filter in the Antiproton Decelerator (AD) facility at CERN to help aid antimatter research.

The notch filter was successfully reverse engineered and then documented. Changes were made in order to increase performance and reliability, and also allow easy integration into the AD. An additional phase was added whereby the notch filter was to be controller via a touchscreen computer, situated next to the filter, allowing engineers to set-up each of the electronic devices used. While one of the devices (Motorised Delay Line) can be controlled by the touchscreen computer, the other two cannot. Due to time constraints and difficulties with the Beckhoff TwincatII programming language, the USB devices were not able to be controlled via the Touchscreen computer and still require the LabVIEW programs.

Overall, the fibre optic notch filter is now in an operational state and can be implemented within the AD, to replace the existing RF notch filter.

2 INTRODUCTION

The Antiproton Decelerator (AD) at CERN is a one of a kind, 'Antimatter Factory'. It allows for the capture of antiprotons, primarily for studying antimatter. Antiprotons are produced by using the Proton Synchrotron (PS), where a beam of protons are fired into a block of metal. Proton-Antiproton pairs are then generated (at a rate of 1 in 1 million collisions) [1]. Often the most difficult stage in anti-atom production is the antiproton stage, these newly-created antiprotons are travelling at close to the speed of light, have a range of energies, and move in random directions. This makes them very difficult to use to make anti-atoms, hence there is a need for cooling. Cooling takes place in several stages, first stochastic cooling, which cools and focuses the antiproton beam. This occurs at 3.57 GeV (Giga-electron-volts) and at 2 GeV. Once the beam has been sufficiently refined, deceleration can take place. However, during this stage, the beam has a tendency to expand [2]. Therefore, the decelerating stage is interlaced with more cooling. A method called "electron cooling" (where the beam is passed through a cloud of electrons) is used for lower energies; this occurs at 300 MeV. When the final energy of the beam is 100MeV, the antiprotons can then be ejected and captured by one of the 3 surrounding experiments - ATRAP, ASACUSA, and ATHENA.
3 NOTCH FILTER (STOCHASTIC) COOLING THEORY

The aim of beam cooling is to reduce the energy spread and overall size of the beam. The goal is to compress (or focus) the beam such that the particles occupy a smaller area. The term "beam cooling" has been taken from the kinetic theory of gases [3]. The mean square spread of the beam is used to define the beam temperature, this is analogous to the temperature of the gas - determined by the kinetic energy of the molecules:

\[ E = \frac{1}{2} m V_{rms}^2 \]  

Hence, the term beam cooling is used to express the increase in beam density. There are two main types of cooling that are used; these are "Electron Cooling" and "Stochastic Cooling", only the former will be discussed in this report. Not all particles need cooling however, for example electron beams need not be cooled as this is inherent in the system - as they orbit the accelerator, they emit (synchrotron) radiation. This radiation is inversely proportional to the increase in mass, meaning heavier particles (such as antiprotons) do require cooling.

(a) General Overview Of Stochastic Cooling

Stochastic cooling is so named because it only affects a certain percentage of particles (also known as a particle bunch) at any one time, and this percentage of particles all receive a "kick" affecting the overall momenta of the particles. Following on from this, it can be understood that the beam cannot be cooled all at once, rather, it takes time to cool all the particles and this time is proportional to the temperature delta that is required. Stochastic cooling uses negative feedback for this beam correction, in the case of this project a notch filter is used.

The process of this negative feedback can be better understood by investigating the example of a single particle.
Figure 1: Horizontal cooling of an antiproton beam, assuming only one particle. The pick-up measures the horizontal deviation, and the kicker then corrects it.

Figure 1 shows how this process works. The solid line indicates the centre of the collector ring, the dashed line shows the path of the particle. The pick-up then senses the particle’s horizontal deviation, and an electronic signal is produced proportional to the magnitude of this deviation. It is then amplified and sent to the kicker, which "kicks" the beam by an angle proportional to the error (deviation from the centre).

To best explain this cooling theory, the antiproton’s oscillation can be approximated as a pure sine wave. The distance between the pickup and the kicker is also very important, since it has to modify the angle on the next cycle. Hence this distance is usually chosen to be a quarter of the antiproton oscillation - or a multiple of this if the distance required is greater.

The ideal case for cooling would be when the peak of the antiproton oscillation lies exactly at the pick-up, as shown in figure 2a. The kicker can then apply the correct perturbation to force the particle into a central orbit. This requires a minimum of 1 full cycle of the collector ring.

A particle that does not have its peak in the pickup will not be completely corrected into a central orbit, the worst case scenario is shown in figure 2b, where the zero crossing point of the sine wave lies exactly at the pick-up. In this case the kicker does not perturb the particle since it appears to be in the central orbit.
In the case of this project, the feedback method used is a notch filter. Usually these are RF notch filters, which are expensive and very large since they need to delay the signal in order to apply the notch filter transfer function, shown below in equation 2 and 3:

\[
S_{21, \text{ideal}} = \frac{S_0}{2} \left( 1 - e^{j\omega T} \right) = -j |S_0| \sin \left( \frac{\omega T}{2} \right) e^{j\omega (t_0 + \frac{T}{2})}
\]

\[
S_0 = |S_0| e^{j\omega t_0}
\]

A correlation notch filter consists of splitting the input signal into two lines with differing electrical lengths. The short branch is the line of the notch filter which is a direct connection to the output, through some fixed attenuation, and it has a delay of \( t_0 \). The long branch has an added delay "T", giving an overall delay of \( t_0 + T \). It is important that both branches have the same attenuation. This is the reason that the design in figure 4 has a variable attenuator in the long delay branch - for fine tuning. The motorised delay line is used also for fine tuning.

The delay time \( T \) should be exactly equal to the nominal revolution period of the beam. Physically, the notch filter response combined with an additional 90° phase-shift, pushes particles with the wrong revolution frequency to the nearest notch and does not affect particles with the nominal revolution frequency.

This project modulates the RF signal onto a laser (therefore making it an \textit{optical} notch filter), which is then sent through fibre optic cable of differing lengths to obtain the delays needed to apply the transfer function. Since the fibre optic cable is somewhat flexible, it can be coiled, reducing the size drastically.

\section{4 Reverse Engineering The Existing Notch Filter}

To begin with, the existing notch filter needed to be reversed engineered. The main method of reverse engineering was to read the serial numbers of the devices used, then using a online search engine to determine the functionality of the device. Datasheets/wiring diagrams could then be acquired to ensure correct functionality. Figure 3 below shows the initial, unaltered notch filter.
5 Upgrading The Existing Notch Filter

Since the notch filter was to be installed into the AD, the programmable power supply had to be removed and replaced with fixed power supply units (PSUs). Each device’s datasheet was consulted to deduce what voltages and what current was needed, so that the appropriate PSU could be ordered. Two 12v, 8A supplies were chosen, making available both +12v and -12v for the electronics. Initially, some electronics were using voltages that were not +12v, however upon closer inspection of the relevant datasheets it was seen that this could be changed to use +12v and still be within specification. So to reduce cost and complexity of the design, it was changed such that all electronics now use a voltage of ±12v. Figure 4 shows an overview of the notch filter.

Figure 3: Notch filter before any engineering work was carried out.

Figure 4: Overview of the optical notch filter
Accompanying each electronic device was a custom made printed circuit board (PCB). The circuit was inspected and found to be a protection (crowbar) circuit. This would prevent any voltage spikes reaching the devices. The crowbar circuit for the variable attenuator was removed, since it was made to short-circuit any voltages above 8.2v. As mentioned previously, the requirements changed such that all electronic devices used ±12v.

Figure 5 below shows how the PCB was originally designed. It should be noted that on this particular crowbar circuit, two of the wires had broken off or had a loose contact - this could have lead to issues in the past.

![Crowbar circuit](image)

**Figure 5:** Crowbar circuit for protection against voltage spikes for the variable attenuator, before PCB mounted screw terminals were installed

The circuit diagram for the crowbar circuit found on the inputs of all the electronic devices is shown below, in figure 6.

![Circuit diagram](image)

**Figure 6:** The Crowbar circuit used for protecting the DC inputs of the Motorised Delay Line (MDL), Optical Transmitter (TX1), Optical Receiver (RX1 and RX2), and the variable attenuator.

The wires for the crowbar circuits were soldered on, meaning that the devices could not be easily maintained or replaced in the event of failure. Therefore, PCB mounted screw terminals were bought that met all the requirements and installed.
Figure 7 shows the new, neater wires installed with the PCB screw terminals.

![Figure 7: The front and back of the new crowbar circuit used to prevent voltage spikes on the transmitter (TX1)](image)

All of the old wires were replaced with colour coded wires, whereby the colour represents the voltage, to help aid maintenance and installation. Red wires are +12v, Black wires are ground (0v), and green wires are -12v. DIN rains were installed to mount the 2 PSUs, 2 junction boxes, and finally a mains box was added. This provided the AC power to the PSUs, with integrated filtering and isolation switch.

Figure 8 shows the layout of the new notch filter.

![Figure 8: The new notch filter design and layout](image)
An overview of the design, indicating what each of the electronic devices are, is shown in figure 9.

![Figure 9: Overview of the fibre optic notch filter, indicating what each of the electronic devices are](image)

6 REMOTE CONTROL OF THE ELECTRONICS VIA LabVIEW

In order to test the functionality of the filter, three devices had to be communicated to using a computer programme. These were the variable attenuator, the motorised delay line, and the TEC (Thermo-Electric Controller). The motorised delay line requires communication over RS-232, the other two can be communicated with via USB. For testing purposes, National Instruments LabVIEW was used. This allowed easy integration between the PC and the electronic devices, speeding up test times.

Again, the datasheets of the many different devices were consulted, and the commands were interpreted. Four separate programs were written, one for each of the three devices and one to launch any of the three programs. All of the programs follow the guidelines outlined in the National Instruments Certified LabVIEW Developer syllabus. The programs used parallel loops (producer/consumer architecture) to ensure there was no data loss, and that any action performed by the user was handled quickly.
(a) The Launcher

The first program written was one to launch the other programs - this allows the user to pin this application to the task bar, and quickly load the relevant programs. It also makes it easier to switch between programs when there are many applications open. Figure 10 shows the front panel for this application.

![Figure 10: Front panel for the Launcher LabVIEW application](image)

(b) The TEC 16-24 Controller

In order for the notch filter to work reliably, the fixed delay line had to be thermally stabilised. Since the transfer function directly relies on the length of the two delay lines, any variation (due to thermal expansion and contraction) will cause significant affects. Hence, the fixed delay line is thermally stabilised via a peltier element. The delay line was opened up after preliminary testing indicated that the thermal conduction between the metal enclosure and the peltier element was insufficient. More thermal compound was added and the height of the peltier element adjust so that it was in contact with the metal enclosure. Figure 11 shows the exposed peltier element.

![Figure 11: Exposed peltier element of the fixed delay line](image)
There are two temperature sensors inside the delay line, one at the base (the black object behind the element in figure 11) and one at the top. Both these sensors are connected to the TEC controller and are used to keep the temperature at a set value. The TEC applies a Proportional-Integral (PI) control loop, and has a variety of commands to help achieve a set temperature. The LabVIEW program allows you to completely configure the TEC, passing the gain parameters of the PI controller, the target temperature, and which sensor to use for the PI controller, as well as many other commands. It also polls the controller for information such as voltage and current usage, errors, temperature values, etc. All this information was vital during testing. The P and I gains were tuned, and then the system was tested by setting a target temperature and seeing how fast it reacted, and whether or not it was stable.

Figure 12a shows the response of the temperature with differing values for the PI controller. It can be seen that initially the overshoot was too large, and the system oscillated widely about the set value. After a few attempts, this oscillation was dampened by removing the integral component. The system was then tested over night, starting from room temperature (24°C), to see if there were any fluctuations from the set point with changing external temperatures. The value chosen for the set point was 30°C, being several degrees above the average room temperature allows easy heating and cooling - giving a better system response.

Figure 12b shows this test, and how a deviation of only ±0.2°C occurs over the duration of 20+ hours. During testing, this showed no apparent change to the notch filter response.

(a) This shows the tests done to obtain the correct P and I gains
(b) This shows the overnight test, proving the system can stabilise the delay line to within ±0.2°C

**Figure 12:** Outputs of the LabVIEW program used for testing

The front panel of the LabVIEW program is shown in figure 13.
Figure 13: LabVIEW front panel of the TEC controller program
(c) The Variable Attenuator

The variable attenuator communicates over RS-232, however since there was not an available RS-232 port on the development PC, a USB-Serial cable was used. Again, the datasheet and manual was consulted and the drivers were written allowing complete control over the device. Figure 14 shows the front panel of this program.

![Variable Attenuator Controller](image)

**Figure 14:** LabVIEW front panel of the variable attenuator controller program

This program allowed the notch filter to be tuned so that each branch of the notch filter had the same attenuation. When this is the case, the notch depth will be at its maximum. The notch depth maximum was found experimentally by increasing the attenuation in steps of 0.2dBs. To find the range of the data set, a method similar to successive approximation was used, starting at a high value and halving it each time. Depending on whether the notch depth increased or decreased determined whether you add a half or subtract half of the current value. It was found that any value above 4dBs no longer increased the notch depth, hence 0.53db (the minimum attenuation the device could supply) to 4dB was the data range.
The results were tabulated and then a 3D graph was plotted. A 3D graph was chosen since the centre frequency at which the notch filter needed to be tuned to was not known. Therefore this test needed to determine how the response (attenuation) of the filter changed with different attenuator set values, at a range of centre frequencies.

Figures 15a and 15b show this.

![Notch Filter Response](image)

(a) Response of the notch filter with a range of centre frequencies

![Notch Filter Response (Side View)](image)

(b) A side view of the graph, showing peaks at around 3.2dB

**Figure 15:** Two different views of the same graph showing the notch filters response to different attenuation set values and centre frequency

From the graphs, it can be seen that the value that needs to be set for the variable attenuator does not change much over the spectrum of centre frequencies chosen. All the peaks lay around 3.2dB, and the average attenuation set value was 3.22dB.

A network analyser (Agilent Technologies, N5230A) was used to test the notch filter and measure the response (S21) and determine the depth of the notches at different attenuations. Figure 16 below shows two S21 plots of the notch filter. Figure 16a shows the filter before tuning, and figure 16b shows the tuned notch filter, with the variable attenuator set at 3.22dB.
The maximum measured notch depth was 59.448 dB, at an attenuation set value of 3.2, a centre frequency of 1.7450 GHz, and with the fixed delay line stabilised at 30°C. This surpasses the specification of 35 dB.

(d) The Motorised Delay Line

The motorised delay line (MDL) was communicated to via RS-232, it occupied the only RS-232 port on the development PC (COM1). This allowed the phase of the filter to be changed, which changes the frequencies that are affected by the filter. In its simplest form, the MDL consists of 2 mirrors attached to 2 motors with precise encoders, allowing the distance to be changed (and therefore allowing the light delay to be extended) by fractions of picoseconds ($10^{-12}$ seconds). Figure 17 shows the front panel of the LabVIEW program that was used.

Tests indicated that a notch of the filter was at 1.300193 GHz (the 818th harmonic), when the MDL
is set to 642 pS delay. This gives a $\Delta$ frequency of 1.589478 MHz between notches, which meets the specification required.

7 INTEGRATION OF TOUCHSCREEN COMPUTER CONTROL VIA TWINCATII

Once all other phases of the project had been completed, a new one was introduced. This entailed integrating an embedded touchscreen PC (Beckhoff CP-2616). It was programmed using Beckhoff’s PLC programming language, TwinCatII. Due to time constraints and unforeseen circumstances with TwinCatII, only the MDL can be controlled using the touchscreen PC. Figure 18 shows the program that is deployed to the embedded touchscreen PC, and was used to control the MDL.

![Motorised Delay Line (MDL-002) MDL-002](image)

**Figure 18:** The program used to control the MDL using the embedded PC.

The TwinCatII program gives all the same functionality as the LabVIEW test program did.
8 CONCLUSION

In conclusion, all of the initial phases outlined have been completed, except phase 4 which was to install the notch filter into the AD for testing with real beam signals. However, the notch filter has met all the required specifications, exceeding them in some areas, and so installation into the AD, and testing via the LabVIEW programs, should not give rise to any complications.

Many lessons were learnt during this project, including furthering the knowledge of: particle physics, heavy ion collisions, notch filters and RF measurement techniques, programming in various languages, and electronics.
Bibliography

