

# The Design and Construction of a Resonance Control System for the IOTA RF Cavity

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**Abstract:** The IOTA ring will be an advanced storage ring used for non-linear beam dynamics experiments to assist in the construction of future accelerators. This ring is being built in conjunction with the FAST electron LINAC and the HINS RFQ proton source for injection into the ring. These accelerators will generate +150 MeV electron beams and 2.5 MeV proton beams respectively. As the beams are injected into the IOTA storage ring their longitudinal profile will begin to smear out and become more uniform. This will prevent detection of beam position with a Beam Position Monitoring system (BPM). To combat this a ferrite loaded bunching cavity is being constructed. This paper details the design and construction of an automatic resonance control system for this bunching cavity.

## 1. Introduction

At the New Muon Laboratory (NML) at Fermilab, the Fermilab Accelerator Science and Technology (FAST) electronic LINAC is being constructed along with the Integral Optics Test Accelerator (IOTA) storage ring and the HINS RFQ proton source. FAST will generate beams of 150-300 MeV electrons that will be injected into the IOTA storage ring for non-linear beam dynamics experiments. In addition, a 2.5 MeV proton beam will be injected into the storage ring at a separate time to test space charge effects. To detect the position of the particles inside of the IOTA storage ring, a Beam Position Monitor (BPM) will be used. However, the BPM requires the beam to be bunched, and after several turns throughout the storage ring the beam will have lost its initial bunching. Thus a bunching system needed to be developed to allow the BPM to detect the position of the particles inside of the storage ring. Due to the nature of the BPM, bunching the beam at 30.62 MHz,  $h=56$ , would be the preferred frequency for this bunching system. This arrangement will work fine for the electron beam, but previous work<sup>[1]</sup> showed that it would not be suitable for the proton beam. The cavity is limited to 1 kV or less on the accelerating gap, and as such could not suitably bunch the proton beam. The solution was then to bunch the proton beam at  $h=4$ , 2.19 MHz, and modulate the bunched beam with the 30.62 MHz RF cavity that is also used to bunch the electron beam<sup>[1]</sup>.

The cavity is an anodized aluminum pillbox that was taken from the now decommissioned Antiproton Source. Inside of the pillbox housing there is a piece of beampipe with two ceramic breaks, which are used as the accelerating gaps. In addition, the housing is split into two with a copper and aluminum separator. This separator decouples the 30.62 MHz bunching side from the 2.19 MHz bunching side. The cavity housing also contains several ferrite disks to further tune the accelerating cavities to the correct frequencies<sup>[2]</sup>. The final tuning will be done with two large, variable capacitors to align the cavities resonant frequency with that of the incoming RF power. These variable capacitors will be controlled via stepper motors to tune the bunching cavities. It was decided that an automatic tuning system would be helpful in this case. The following paper details the design, construction, and preliminary implementation of such a system.

## 2. Experimental Details

The project consisted of two major components; software design, and integrated systems testing. In addition, the software design focused on the integration of the PLC control software with the

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Fermilab Accelerator Controls Network (ACNET), along with the development of a controls loop for the automatic RF tuning.

The hardware for this project consisted of a P2-550 Programmable Logic Controller (PLC), Two STP-DRV-4850 stepper motor drivers, a P2-AD08 Analog to Digital Converter, and two P2-SCM serial communication modules all of which are from Automation Direct. In addition, two LP-100A Vector RF Watt-meters along with two ten-turn potentiometers and the requisite power supplies. The system configuration can be seen in Figure 1.

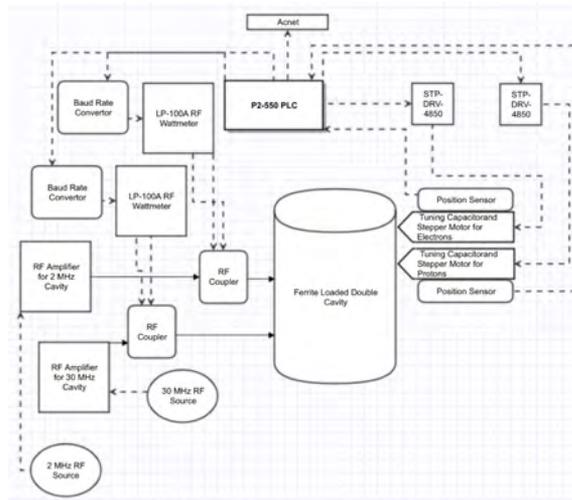


Fig. 1. IOTA Bunching Cavity Controls System Diagram

## 2.1. Software Design

To continuously keep the IOTA bunching cavity at the same resonance frequency as the incoming RF power, a controls loop had to be built. In addition, this controls loop had to be integrated with the Fermilab ACNET system and allow for operator intervention, along with sending the operators alerts and updated data about the state of the bunching cavity. The loop could also not be allowed to oscillate around the set frequency. This would induce other problems farther down the line in the IOTA ring. To address this oscillation problem a Proportional, Integral, Derivative (PID) control loop was chosen to damp any destructive oscillations in the control loop. The controls software ladder diagram can be found in the appendix of this paper.

### 2.1.1. PID Loop

PID loops are well known control mechanisms for industrial processes. The basic idea stems from the following equation;

$$(M_n = K_c * e_n + K_i * \sum_{i=1}^n e_i + K_r * (e_n - e_{n-1}) + M_o)^{[3]}$$

The equation starts by taking the error ( $e_n$ ) between the desired value (also called the set-point) and the current value (also called the process variable) and multiplying it by a constant,  $K_c$ . This is the proportional part of the PID loop, however relying just on this portion will result in continuing oscillations around the set-point. In the next portion of the loop another constant, ( $K_i$ ), is multiplied by a summation over all of the previous errors. This allows for the loop to accelerate towards the set-point more quickly and eliminates steady state errors in the proportional control part of the loop. That part of the loop is referred to as the integral portion. The final part of the loop takes the current error and subtracts the previous error from it. This value is then multiplied by a constant, ( $K_r$ ), to generate the derivative portion of the loop. The derivative portion is used to "preact" or predict the upcoming error and preemptively correct for it. It is not always needed, but in especially noisy systems it can be extremely useful. In addition, there is a bias term, ( $M_o$ ),

that can be used to initially offset the loop output, ( $M_n$ ), from zero. It was not found to be useful in this case.

Two PID loops were devised, one to control the proton bunching cavity and one to control the electron bunching cavity. This loop system was engaged every half a second after the data was read from the RF Watt-meter. Then the output was formulated and packaged as a string to be sent to the stepper motor controller.

### 2.1.2. ACNET Integration

It was found that the best method for integrating with ACNET was to use Modbus protocol. This system works natively with the P2-550 PLC, which greatly simplified everything. The Modbus addresses were assigned inside of the program and then sent to the Fermilab Accelerator Division, along with ACNET names, to be put into the ACNET system. Then the PLC was configured to accept input on one of the side Ethernet ports, so that data could be transferred back and forth between ACNET and the PLC. All of the data was multiplied by 100 and saved as an integer. This allowed for ease of sending data to ACNET, without comprising data quality by dropping the numbers past the decimal place. In addition, the PLC was configured to save pertinent data every half of a second, which lines up with the timing of the RF Watt-meter sampling.

### 2.2. Integrated System Testing

To test the system it was installed onto a partially constructed version of the IOTA bunching cavity, Figure 2. This cavity was up to air, and had only one ceramic break and one variable capacitor. In addition, it had 3 ferrite cores and 4 copper cooling plates to help simulate the proper loading. 3 small, 200 pF, capacitors were used to couple the RF power into the cavity. Also, the variable capacitor was attached in parallel to the coupling capacitors to allow for tuning.

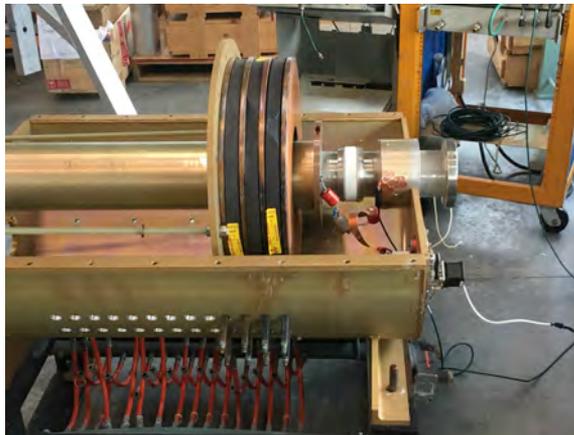


Fig. 2. IOTA Cavity Test Configuration without Cover Installed

The variable capacitor, stepper motor, and ten-turn potentiometer were all attached to a stainless steel bracket along with a 6 inch long belt and pulley system to transmit mechanical power. The entire assembly was then grounded to the outer shell of the bunching cavity.

RF power was then applied across the gap and the system roughly tuned so that the ideal phase for resonance was in the middle of the range for the variable capacitor and the ten-turn potentiometer. The phase in this case is the phase between the voltage and the current across the gap. This was picked to be a phase of 1 degree for the testing that was done, but the ideal phase will most likely be changed in the final implementation. The ideal phase was picked by applying low amounts of RF power (1-5 watts) and then tuning until the Standing Wave Ratio (SWR) was as close to 1.0 as possible. Then 10 watts or greater were applied to the gap to allow for final testing. At this point various aspects of the control system were tuned and tweaked. In addition, the system was

made to respond to several excursions by rapidly changing the frequency and checking for PID and phase response.

### 3. Results

Initially this system did not include a potentiometer to check for the position of the stepper motor relative to the variable capacitor. The initial program just counted the number of steps and then shut off at a certain number from 0. This system was found to be inaccurate and dangerous to the capacitor, thus the ten-turn potentiometers were installed and attached to the P2-08AD Analog-to-Digital Module. This allowed the potentiometer to be accurately read to one part in 65535. The potentiometer was then centered along with the variable capacitor. Thus an output of 32767/32768 would show that the tuning system was centered. Then two layers of safety were programmed into the controls software. The first was a basic safety that stopped the motor, PID loop, and string packing loop when the reading on the potentiometer reading was 65535 or 00005. In addition, an alarm is then sent to the operators to let them know that a limit has been hit. The second safety was programmed after extensive experience tuning the PID loop. It was found experimentally that the PID loop could be tricked into chasing the noise of the RF cavity, if the input noise was especially high for a moment. To combat this "soft" safety's were programmed in at 55535 and 10005. If these safety's are encountered the program then kicks the motor back one full turn, resets the PID loop, and sends an alarm to the operators via ACNET. After the installation of the hard and "soft" limits to combat PID errors and keep the variable capacitor safe, work then turned towards tuning the PID. From previous reading<sup>[3]</sup>, it was found that starting values of  $K_c = 5$ ,  $K_i = 65535$ , and  $K_r = 0$  would be the ideal starting values to begin tuning. At these values the tuning system continued to oscillate around the set-point. Figures 3 and 4 show this version of the PID loop responding to an the cavity being set out of resonance.

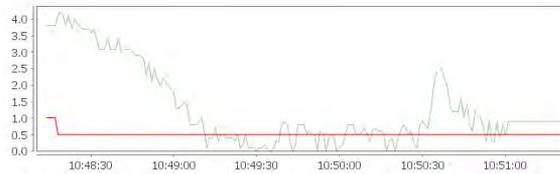


Fig. 3. Phase vs. Clock Time for the Process Variable in Green, Set-Point in Red

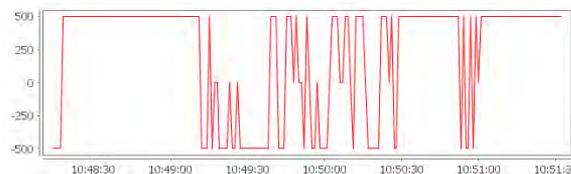


Fig. 4. Steps of Motor vs. Clock Time

Further experimentation proved fruitless, so the program was then set to use an automatic tuning mechanism. This subroutine would take the process variable to both extremes and then back to the middle point in an attempt to characterize the response of the cavity. Then the values for the constants could be determined mathematically. The auto-tuning subroutine was allowed to run several times, both with and without derivative constants allowed. Initially the constants were found to be  $K_c = 0.764$ ,  $K_i = 7$ , and  $K_r = 0$ . However, these constants proved unsatisfactory due to the continued oscillations of the process variable around the set-point. New values were then found when the system was allowed to auto-tune for a derivative constant in addition to the proportional and integral constants. The following values;  $K_c = 0.764$ ,  $K_i = 6.6$ , and  $K_r = 1.1$  were

found to be the smoothest setting for the PID loop. At these values the loop quickly responded to excursions and easily come to zero, with small perturbations due to noise in the cables. Figures 6 and 7 clearly show the easy and fast response of the final PID loop to two excursions (instances when the cavity becomes rapidly out of resonance) that were artificially created by changing the frequency of the RF output.



Fig. 5. Phase vs. Clock Time for the Process Variable in Green, Set-Point in Red



Fig. 6. Steps of Motor vs. Clock Time

This test went on for several minutes, and was repeated several times, and each time the controls system brought the cavity back with 0.1 degrees of phase. It was decided that being within 0.5 degrees of proper phase, with little to no oscillations, would be acceptable for this application<sup>[2]</sup>. In addition, the controls system usually stayed right on a phase of 1.0 degrees and only varied slightly due to system noise. However, the proper PID tuning, combined with the "soft" safeties, kept the loop from chasing the noise of the RF cavity.

## 4. Conclusions

The automatic resonance tuning mechanism for the IOTA bunching cavity has been successfully demonstrated. After several iterations the program has been shown to work in the noisy environment of the test set-up. This shows the readiness of the auto-tuning system because the final installation will most likely be far less noisy. Assuming continuous funding and work levels are maintained, the auto-tuning system will be installed on the IOTA storage ring by the end of 2016. Then in 2017 it will be fully utilized when the IOTA ring is first injected with 150 MeV electrons.

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## References

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