Measuring Longitudinal Bunch Shape in the Fermilab Linear Accelerator with a Feschenko Bunch Shape Monitor

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A Feschenko Bunch Shape Monitor (or bunch length detector) has existed in the 400 MeV section of the Fermilab Linear Accelerator (Linac) for approximately twenty years. Bunch length detectors are a useful and physically simple tool for monitoring the health of a particle beam via longitudinal bunch shape measurements. Secondary electrons in the H^- beam are accelerated away from the beam by a wire supplied with a negative high voltage into a radio frequency deflecting cavity to transform a time profile measurement into a spacial profile measurement. We discuss the operational methods of a bunch length detector and the different types of hardware and how they are controlled to allow for bunch length measurement. Unfortunately, measurements in the Fermilab Linac were not possible because the Accelerator Division schedule did not allow an access to the Linac tunnel until the last week of this project. Some unresponsive hardware was suspected to be malfunctioning in the tunnel throughout the summer; we were able to identify these with an access opportunity during the last week, allowing for measurements to occur soon. Therefore, our discussion also includes methods which allow for testing the bunch length detector in preparation for taking actual measurements from the beam. We also discuss methods for the development of an X-ray based version of a bunch length detector, as opposed to the secondary electron method of our bunch length detector. This method is a future research and development effort towards Fermilab's future accelerator program.

I. INTRODUCTION TO BUNCH SHAPE MONITORS

The Bunch Shape Monitor (BSM) was developed in the 1980's at the Institute for Nuclear Research (INR) in Russia [1]. Laboratories such as CERN, DESY, and Fermilab have installed BSM systems in their linear accelerators for various uses including longitudinal bunch length measurements, three dimensional beam shape measurements, and monitoring beam health [2–4].

The functionality of the BSM is made possible by the ionized state of the particles which make the beam, and the relatively small β of the particles. A thin wire at a negative electric potential is placed inside the beam pipe and the ion beam impinges on it. Secondary electrons are ripped from the wire and accelerated away in a radial manner by the wire's large, negative electric field. These electrons maintain the same time structure of the ion beam. Some of the electrons pass through a slit into a radio frequency (RF) cavity which oscillates at a voltage

$$V(t) = A\cos(\omega t + \phi), \qquad (1)$$

where ω is an integer multiple of the beam bunching frequency and ϕ is a controllable phase [5]. The RF deflecting cavity transforms measurement of the electrons from time to space. The spacial disribution as the same shape as the time distribution. A second set of plates that are set to high voltage by direct current (DC) are available to focus the beam of electrons. These plates are used because electrons are not necessarily going straight through the slit, but may have an angled trajectory. The DC plates can focus these electrons towards the second slit. Figure 1 provides a graphical representation of a bunch shape monitor and the process secondary electrons follow. The second slit is much more narrow than the profile of the beam that the electrons spacially represent. To increase the measurement resolution, the phase of the RF cavity is changed so that different parts of the beam profile are sent through the second slit. Therefore, the bunch signal is a function of the phase difference, $\delta\phi$. Figure 2 provides a theoretical model of signal from a bunch shape measurement. Real beam will not be as perfectly Gaussian shaped as shown in Figure 2.

II. ACCELERATING PARTICLES AT FERMILAB

A. The Fermilab Accelerator Complex

The Accelerator Complex at Fermilab consists of a number of machines used together to accelerate protons to extreme energies. Negatively charged hydrogen ions (H^-) are created in a magnetron-based ion source and initially accelerated by a 750 MeV radio frequency quadropole (RFQ). The H^- beam propagates through the Linac towards a carbon foil, reaching 400 MeV. The beam passes through the carbon foil yielding only protons. The protons are brought into the Booster, a syn-

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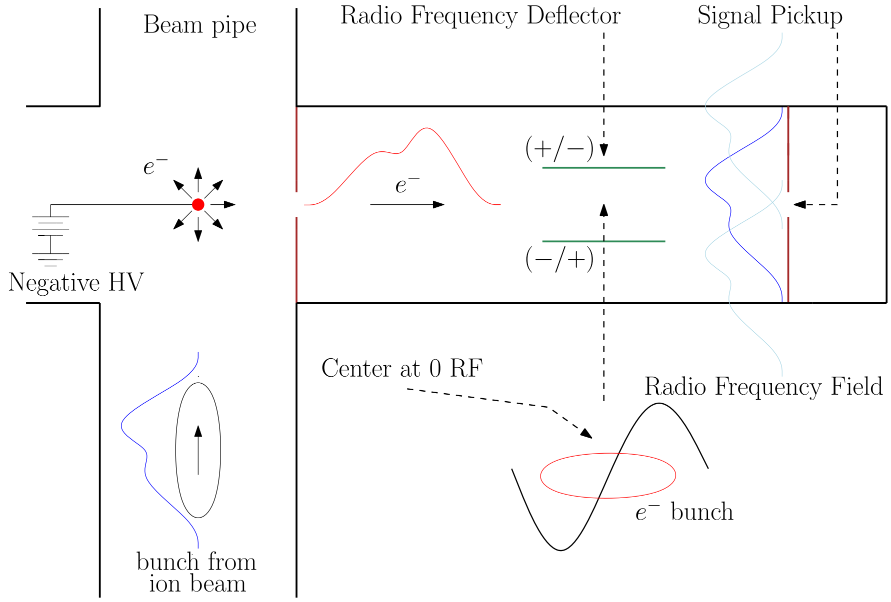

FIG. 1. A schematic of a bunch shape monitor. The ion beam in blue impinges on the wire generating secondary electrons. The wire is kept at a high negative voltage to accelerate the electrons. The secondary electrons pass through the first slit and into the RF cavity. After propogating through the RF cavity the electrons have been transformed into a spacial organization where they can pass through the second slit and into the EMT. Shown in faded blue are bunch profiles that have been phase shifted so that the center of the bunch does not arrive through the slit, a different portion of the bunch does. The green deflector plates are given a DC high voltage to focus and steer the electrons on to the second slit.

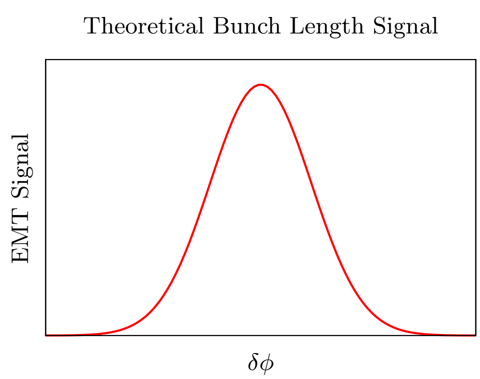

FIG. 2. A theoretical model of the signal from a bunch shape monitor. The signal from the EMT is a function of phase difference $\delta\phi$ because different portions of the beam profile propgate through the slit as the RF phase is shifted. The different portions of the profile then form the full profile when plotted as a function of the phase difference.

chrotron which accelerates the beam to 8 GeV. Protons from the Booster ring are then transferred to the Main Injector, another sychrotron, or spilled into the Booster Neutrino Beamline to collide with a target and create neutrinos. The protons that leave the Booster to continue on in the accelerator chain are brought to 120 GeV by the Main Injector. In the era of the Tevatron, some protons would be sent to the anti-proton production facility where the protons would collide with a target, creating anti-protons. The anti-protons would be sent bac to the Main Injector. Protons and anti-protons would then be transferred to the Tevatron, where they would reach center-of-mass energies of 1.96 TeV before colliding with each other in $p\bar{p}$ annihilation in the Collider Detector at Fermilab or the DØ detector. Beginning with the next run of the the accelerator complex, the Tevatron will no longer be used, and the Main Injector will provide protons to various neutrino experiments by spilling beam to the NuMI (Neutrinos at the Main Injector) beam line, where the protons will collide with a target to create a very intense neutrino beam.

The number of transitions that particles potentially could step through in the accelerator complex introduces the need for each accelerator in the process to maintain a healthy beam. If there is a problem in the beam in an early step, that problem can be multiplied in later steps of the chain. Therefore, the health of the Linac beam is very important.

The future of Fermilab's experimental program consists of a number of experiments needing a high intensity beam. Beam health is essential to maintaining high intensity; therefore, investigating more efficient BSM technologies for future Fermilab Accelerators is important for the Accelerator Program.

B. The Linear Accelerator

The Fermilab Linear Accelerator is composed of two main sections [6]. The first section is a drift tube linac based on the accelerator built by Luis Alvarez at Berkeley in 1947. The drift tube linac operates at 201.25 MHz and accelerates the beam to 116 MeV. The second section of the Fermilab Linac is the side-couple cavity linac which operates at 805 MHz and accelerates beam to 400 MeV.

III. FERMILAB LINAC BUNCH LENGTH DETECTORS

A. Description of the Detectors

At Fermilab, the bunch shape monitors which have been developed are called Bunch Length Detectors (BLD). For the remainder of this report we will refer to the system as such. Multiple BLD's were commissioned at Fermilab in the the early 1990's [4]. This report focuses on a specific bunch length detector currently installed on the linear accelerator, Bunch Length Detector 3 (BLDØ3). BLDØ3 contains a tungsten wire which can be inserted into the beam and retracted out when not in use. It also combines the RF deflector and the DC lens plates into a single unit. The advantages of this setup include the ability to place the deflector very close to the target, and multiple scattering is prevented by the negative DC potential applied to the lens which affects the RF deflector [4]. BLDØ3 is installed in the transition area of the Linac, where the bunching frequency increases from 201.25 MHz to 805 MHz.

B. Controlling BLDØ3

The BLD has many components which need to be set and read-back for monitoring and data acquisition. A 10 watt, 805 MHz RF signal is supplied to the BLD deflecting cavity. The phase of the RF signal is changed using a stepper-motor driven trombone delay line. The two DC focusing plates are controlled by two individual HV supplies. The tungsten wire is given power by a HV supply, and is also connected to a current supply. The current supply allows for thermal emission of electrons from the wire for testing without beam.[1] A motor to move the wire in and out of the beam is also needed. Gate signal is used to power the RF cavity only when a Linac beam pulse is occurring (the Linac pulses at 15 Hz). The electron multiplier tube is also powered by a HV supply. Figure 4 provides a graphical representation of the hardware which powers and controls the BLD and also the hardware that supplies the readout.

Fermilab's `Accelerator Control Network` (`ACNET`) is the main tool used for these tasks. `ACNET` is a unified control system for the entire accelerator complex, controlling each accelerator and all technical equipment [7].

[1] Details of this procedure are discussed in section IV B

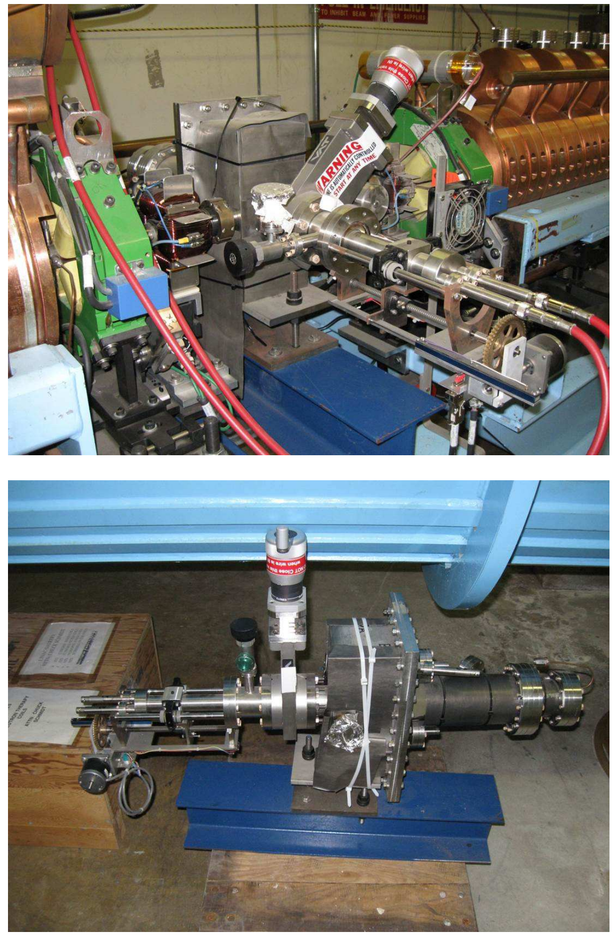

FIG. 3. Two digital camera photos of the Bunch Length Detector currently installed in the Fermilab Linac. The top photo shows the BLD installed on the beam line. The bottom photo shows the BLD detached. In the bottom photo various parts are visible. The aluminum foil represents where the BLD received beam. The left side shows the motor for the wire position, the right side consists of the RF cavity and the far end EMT.

`ACNET` allows for single devices to be established as parameters. Parameters are given an 8 character name and can be set, read, and given a prescribed alarm value. An `ACNET` parameter page has been established which houses the parameters for BLDØ3. Table I includes a list of all parameters that are related to BLDØ3.

C. Data Acquisition

To collect data from the electron multiplier tube at different phase difference values, a script has been written in the `Accelerator Control Language` (`ACL`) [8]. `ACL` allows for automated control (setting and reading back) of `ACNET` parameters, while also performing as a powerful scripting language with utilities common to most regularly used, modern programming languages. It is advantageous to use `ACNET` and `ACL` simultaneously. `ACL`

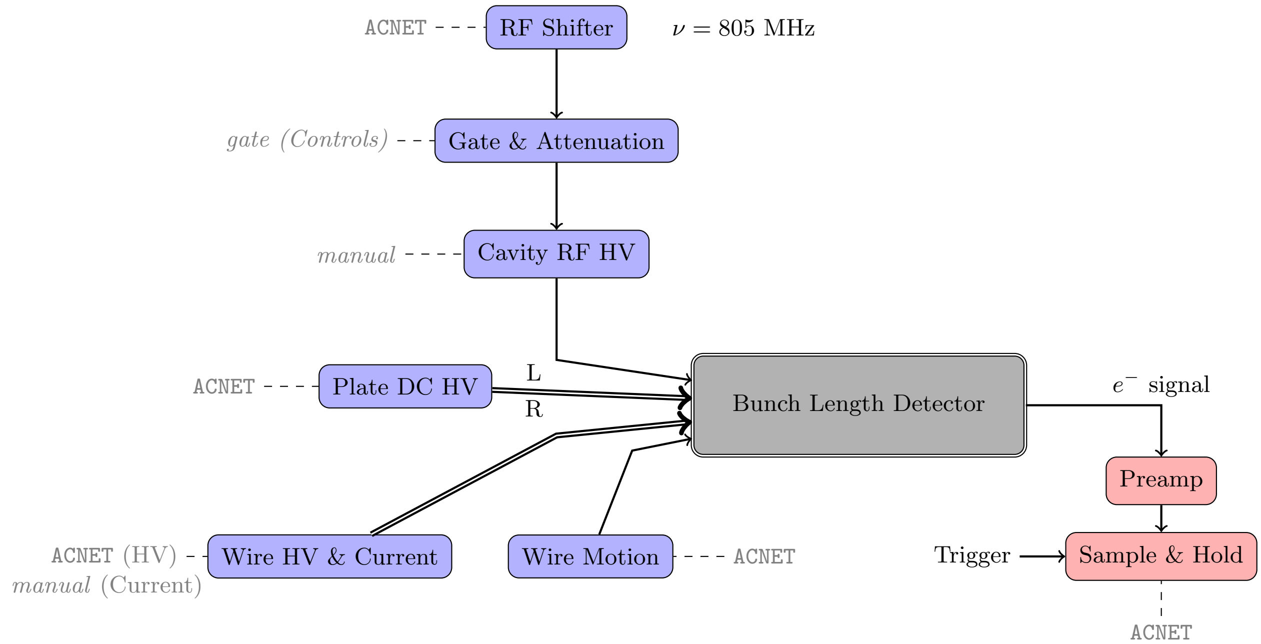

FIG. 4. A simple block diagram of the Fermilab BLD system. Items in blue are controlled parameters. Items in red receive signal from the BLD. Gray labels represent the way in which the blue parameters are controlled and the red parameters are read out. In this diagram we consider the EMT as part of the Bunch Length Detector, it is controlled manually by a high voltage supply.

TABLE I. A list of all parameters for BLDØ3 and there function. These parameters exist on page `L20` of `ACNET`. The page contains parameters for all BLD's at Fermilab. We focus on BLDØ3 here because it is the subject of this report.

Parameter Name	Function	Can be set / Can be read
`L:D03BDM`	Tungsten wire position	Yes / Yes
`L:DDMOT1`	Stepper Motor I	Yes / Yes
`L:DDMOT2`	Stepper Motor II (non functional)	No / Yes
`L:DDMOT3`	Stepper Motor III	Yes / Yes
`L:DDMOT4`	Stepper Motor IV	Yes / Yes
`L:D03BDS`	The electron multiplier tube signal	No / Yes
`L:D01WHI`	The tungsten wire high voltage current	Yes / Yes
`L:62FT07`	The sample and hold trigger for the electron multiplier tube signal	Yes / Yes
`L:D03WHI`	The tungsten wire high voltage maximum current	Yes / Yes
`L:D03WHV`	The high voltage setting for the tungsten wire	Yes / Yes
`L:D03HI1`	The maximum current for the left lens DC supplied plate	Yes / Yes
`L:D03HV1`	The high voltage setting for the left lens DC supplied plate	Yes / Yes
`L:D03HI2`	The maximum current for the right lens DC supplied plate	Yes / Yes
`L:D03HV2`	The high voltage setting for the right lens DC supplied plate	Yes / Yes
`L:BLDRFG`	The gate delay for the BLD system	Yes / Yes
`L:BLDRFW`	The gate width for the BLD system	Yes / Yes
`L:BLDRFE`	The gate event for the BLD system	Yes / Yes

can be used to give automated commands to `ACNET` parameters, while the user can interactively use `ACNET` to monitor parameters. The algorithm for taking data from the EMT as the stepper motors were phase shifted is as follows:

```
declare read list containing:
  phase value
  emt signal
while ( i < DesiredSteps ) {
  while ( j < 10 ) {
    wait for linac event {
      read parameters in the read list
      store values to file
    }
    j++
  }
  step phase
  i++
}
```

The above algorithm allows for automated data collection corresponding to taking 10 data points for each RF phase value. The phase value and signal are stored so that phase difference values can be calculated using each value, and a profile of the beam can be made consistent with Figure 2. A single EMT signal is created from each Linac pulse (15 Hz), the bunch shape is then created from many beam pulses.

D. Radio Frequency Deflector System

The radio frequency deflector system is the most important part of the BLD. Without a shift of the phase, only a small part of the electron density would propagate through the second slit, and a bunch length would not be able to be determined. There are many components that contribute to the function of the RF deflector system. We will refer to Figure 5 during the following explanation of the RF cavity system [4]. The two arms labeled **1** form a resonant cavity. The input RF power is provided by a coupling loop, labeled **2**. Another loop, **3**, provides read-back. The resonant frequency of the cavity can be tuned by adjusting the end-caps, **4**, and by trimming the deflector plate size, **5**. The final resonant frequency is provided by slug tuners, **6**. The point of zero RF is at **7**, which is where the DC voltage for the lens is applied, along the center conductor of the coaxial arms. The voltage is applied through a 1 MΩ resistor, **8**. The secondary electrons pass through and are focussed at **9**, the central region of the deflector. The deflector arms are supported by **10**, nylon rings. The frequency of the RF cavity in BLDØ3 is the first harmonic of the bunching frequency in the 400 MeV section of the Linac. Therefore, the frequency in Eq. (1) for BLDØ3 must be 805 MHz to function properly.

IV. HARDWARE PREPARATION & TESTING

The bunch length detectors in the Linac have not been in operation for many years. Therefore, we had to familiarize ourselves with all of the difference hardware devices and also test and/or callibrate them. We also developed a method to determine how to set the DC voltage plates for focussing the secondary electron beam. This section discusses that method, and also the processes completed to test some hardware devices.

A. Measuring the Resonant Frequency of the RF Cavity

The resonant frequency of the RF cavity needed to be measured to ensure that the cavity was at the first harmonic of the Linac bunching frequency. To check the resonant frequency, an Agilent Network Analyzer was used to send an array of frequencies between 800 MHz and 810 MHz. The output response was a dip at 805 MHz, confirming the needed frequency.

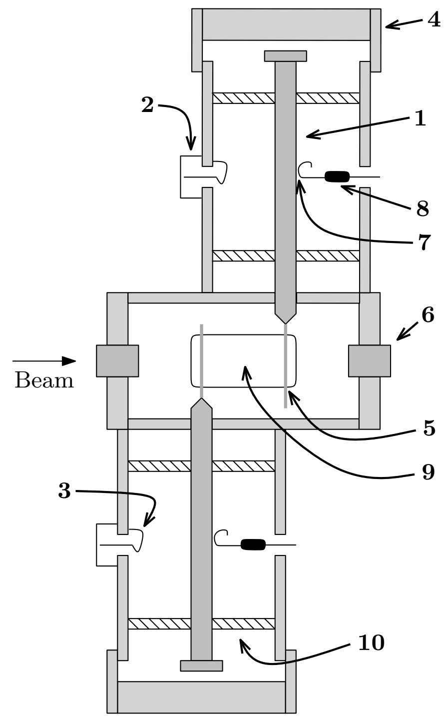

FIG. 5. Diagram of the RF cavity deflector system. The system is described in detail in Section III D. The beam in this diagram is the actual H^- beam, secondary electrons propagate perpendicular to the page. The two arms are mirrors of each other; therefore, each part is labeled once but has a corresponding identical part on the opposite arm.

B. Preparing the DC plate lens system

We previously described that it is possible to supply a current to the tungsten filament. This current is unnecessary when the wire is in the beamline, because the beam will impinge on the wire and electrons will be accelerated away. However, the current is useful for determining how to set the voltage for the DC plates that focus the secondary electron beam. With the wire in the beamline, but without beam running, the current can be applied and electrons will "boil" off of the wire.[2] These electrons will act as the secondary electrons do and be accelerated away through the slit. We can supply the current, and step the voltage applied to the plates while monitoring

[2] The wire must be in the the position of "in the beamline" because that is the location the wire would be when running beam and measuring bunch length. If the wire were out of the beam, an incorrect voltage would be determined (that voltage would correspond to an incorrect beam position).

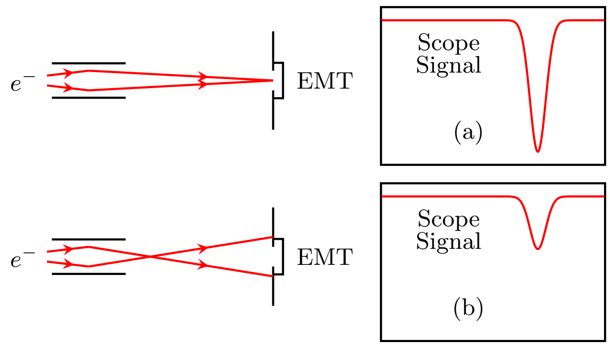

FIG. 6. Two examples of using the DC supplied plates as lenses to focus the secondary electrons towards the slit at the far end of the cavity. (a) represents an ideal focussing, where the electrons impinge on the middle of the slit, and a good signal is received at the EMT. (b) represents a bad focussing, where the electrons are over-focussed and a good signal is not received by the EMT.

the EMT signal simply via an oscilloscope. If the electrons are not focussed enough, the signal will be low, and the same happens if the electrons are over-focussed. By stepping the voltage, we determine when the electrons are focussed correctly. Figure 6 provides two examples of focussing the plates for ideal EMT signal.

C. Stepper Motor Tests

The stepper motors were tested to check the linearity of the motors and to determine the resolution we would have when shifting the RF phase value. Testing the stepper motor linearity also allowed for us to determine the relationship between the number of steps and the phase shift. A smaller algorithm similar to the one described in Section III C was used to step the motor and record the phase value. As described in Section III B, there are multiple stepper motors set up in the Linac Diagnostics room. Here, we present data taken from stepper motor `L:DDMOT3`; that is the motor currently arranged to shift the phase of the RF cavity in BLDØ3.

The natural frequency of the stepper motors is that of the first section of the Linac, 201.25 MHz. Therefore, as the motors were stepped, the frequency read back from `ACNET` corresponded to a resonant frequency of 201.25 MHz. At this frequency, we tested the linearity of the stepper motors, results are present in Figure 7a. We created a histogram of the distance from each point to the fit in Figure 7b. The RMS of this histogram tells us the phase resolution.

Because the Linac operates at a bunching frequency of 805 MHz, we retested the stepper motors after passing the output from the motor through an Agilent Network Analyzer, which was calibrated to readback phase values in degrees corresponding to an 805 MHz resonant frequency. Linearity and point to fit histogram plots are displayed in Figures 7c and 7d. Because of our confidence in the linearity from the previous tests at 201.25 MHz, less data points were recorded.

V. HARDWARE TESTING AFTER LINAC ACCESS

After a controlled access to the Linac, certain connections in the tunnel and in the Linac Diagnostics Room were discovered to be inconsistent. These inconsistencies were identified to correct our understanding of the hardware connections in the Linac and in the Diagnostics Room.

A. Generating a Signal

The high voltage power supply used to set the filament at a high negative electric potential had one of the inconsistent connections. Upon identification, we were able to supply the potential and current to the wire to boil electrons away. This fix allowed for the generation of a signal on the EMT. We supplied approximately 1 A of current, while keeping the filament at -10 kV. A plot of the EMT current as a function of supplied voltage is in Figure 8. We conclude that an ideal voltage during BLD operation is 2200 V.

VI. X-RAY BASED SYSTEMS

Secondary electron based bunch length measurement (or as earlier stated, bunch shape measurement) systems are subject to the effects of ion beams carrying two electrons. The H^- beam has two electrons that can also be accelerated away along with electrons from the filament [10]. These electrons have forward momentum heavily in the beam direction; therefore, those that propagate through the slit are later arriving compared to the electrons from the wire. These electrons create a tail in the profile. For lower energy ion beams, this effect is larger.

The future of the Fermilab Accelerator Complex includes the development of a new lower energy, high intensity accelerator [12]. Therefore, a research and development effort is going to be made towards the development of an X-ray based bunch length detector to eliminate the noise-effects that a secondary electron based bunch length detector has.

In an X-ray based BLD, the ion beam impinges on a foil or gas target instead of a wire. When the ion beam impinges on the target, electron shell vacancies are created in the target atoms, causing emission of X-ray photons. The photons propagate through a slit and strike a photocathode, where photoelectrons are created and propagate through an RF cavity, similar to the secondary electron based BLD. The phase shifted electrons strike an electron

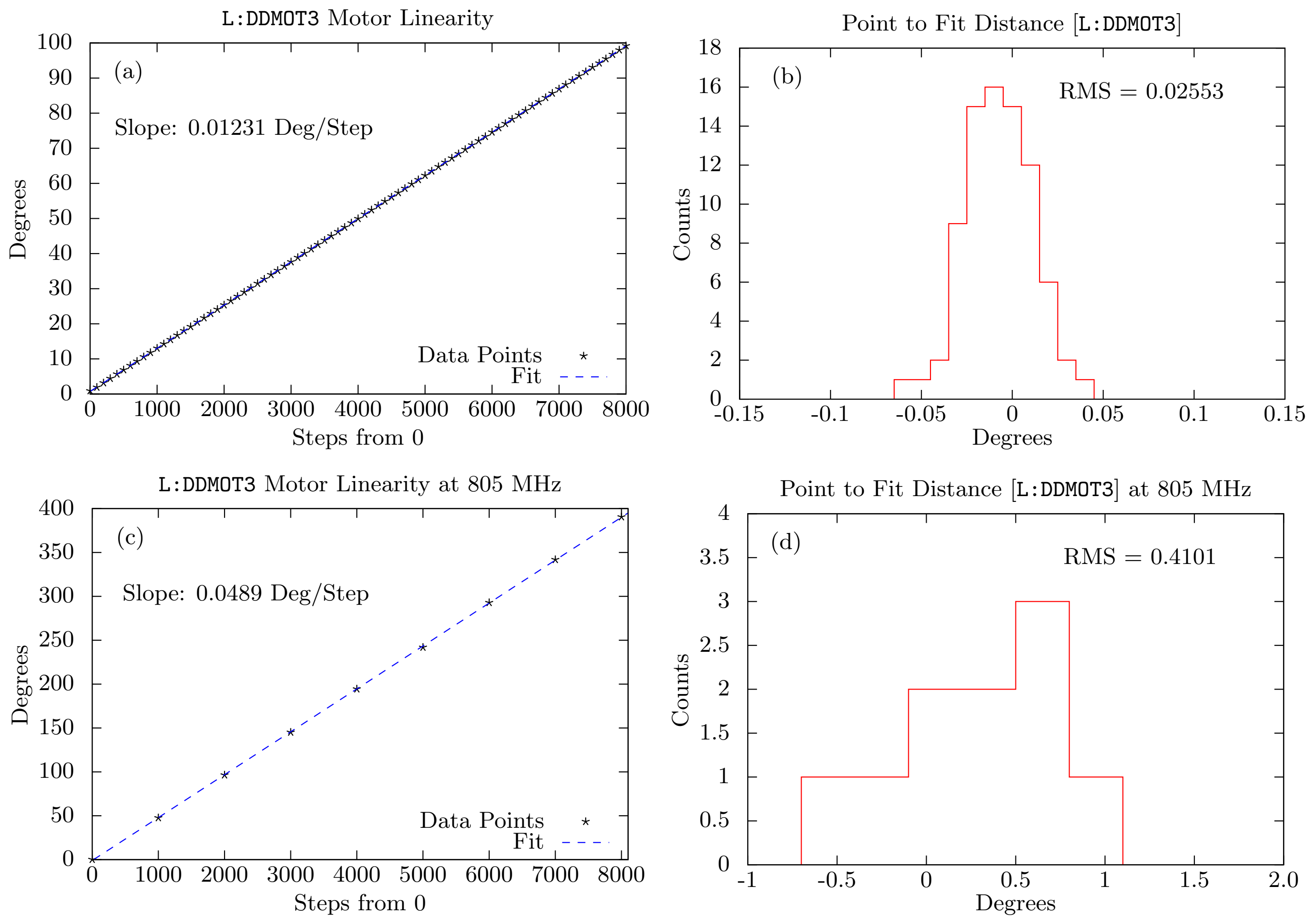

FIG. 7. Linearity plots for one of the stepper motors, `L:DDMOT3`, and histograms to determine the phase resolution of the motor at 201.25 MHz and at 805 MHz. The RMS of the histogram in (b) reveals a phase resolution of approximately 0.025 degrees. This is sufficient for bunch length measurements.

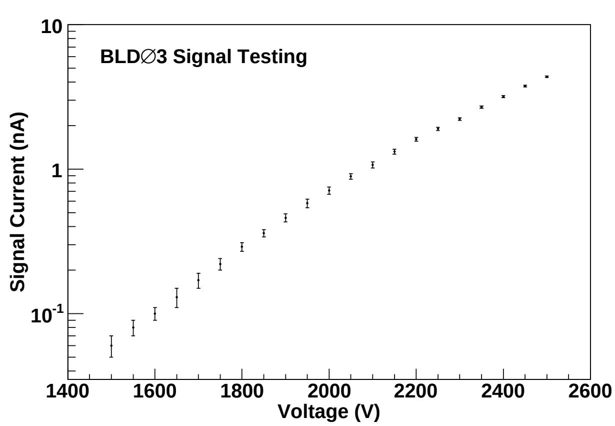

FIG. 8. Signal current in the EMT as a function of the EMT voltage

detector, again similar to the secondary electron based BLD. A diagram of the process is given in Figure 9.

Upon the completion of recommissioning the secondary electron based BLD installed on the Linac now, it will be removed and converted into an X-ray based BLD and reinstalled. Studies with the X-ray based BLD on the Linac will be the first stage of research and development towards an X-ray based BLD for future low energy, high intensity accelerators at Fermilab.

VII. CONCLUSIONS

We have discussed how secondary electron based bunch shape monitors operate, and the status of the recommissioning of the bunch shape monitor in the Fermilab Linac. Throughout the summer we worked towards making bunch shape measurements by testing hardware and developing a simple method for data aquisition. Unfortunately, the Linac was not able to be accessed until late in the summer. We were fortunate in finding problems we were blind to before the access. After identifying problems, we were able to run some small tests, and we are

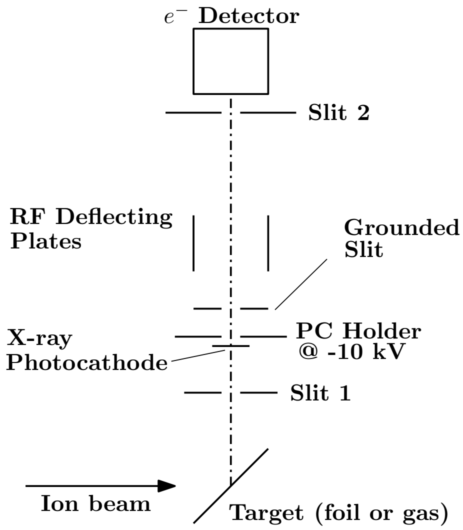

FIG. 9. X-ray based BSM diagram. The method is very similar to the secondary electron based BSM. The two main differences are the substitution of the the wire for a foil or gas target, and the addition of the photocathode to produce electrons from the x-ray photons.

now very close to being able to measure real Linac bunch shape. We also discussed other testing methods.

The future Fermilab Accelerator Program will include a low energy, high intensity beam. Therefore, we discussed the function of an X-ray based bunch shape monitor, which is of interest to the research and development effort for the new complex. We plan to remove the secondary electron based bunch shape monitor once it has been fully recommissioned and used,then replace it in the Linac with the X-ray based BSM. This will allow research and development of the X-ray based BSM. In the future, an X-ray based BSM will be installed in PXIE to prepare for Project X based on the use of the BSM in the Linac.

VIII. ACKNOWLEDGEMENTS

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