ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLO16

ENERGY SPREAD MEASUREMENTS FOR 400 MeV LINAC BEAM AT FERMILAB BOOSTER USING A LASER NOTCHER SYSTEM*

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Abstract

To mitigate 8 GeV beam losses at extraction in the Fermilab Booster synchrotron, a LASER chopper system for multi-turn injection that produces a beam free gap, aka "notch" in the LINAC beam pulse at 750 keV is developed. These notches in the LINAC pulse are spaced with the 400 MeV injection revolution period of the Booster. Recently, a dedicated notching pattern that keeps a single 201 MHz LINAC bunch in the middle of a notch is developed to measure the beam energy spread by studying the time evolution of this bunch in the Booster. A method complementary to this has also been realized by injecting <2 Booster turn beam and studying the time evolution of the multiple 201 MHz LINAC bunches. In this paper we present the general principle of the method and results from our measurements.

INTRODUCTION

Recently, Fermilab executed a "Proton Improvement Plan" [1, 2] to upgrade the existing accelerator complex to meet its high intensity proton demand for accelerator-based neutrino experiments. This effort had a baseline goal to extract the beam at a 15 Hz rate from the Booster with about 4.6E12 p/Booster cycle. This allowed the delivery of > 700 kW beam power to the NOvA target while supplying record beam power to the 8 GeV short base-line neutrino program. With the completion of the PIP-II [3], the Booster beam delivery will be upgraded to 20 Hz and the normal conductor 400 MeV injector LINAC will be replaced with an 800 MeV superconducting RF LINAC increasing the injected beam intensity by about 50% allowing the capability to provide 1.2 MW beam power to the new LBNF/DUNE experiment.

Between now and when the PIP-II LINAC comes on line, Fermilab will continue improve the accelerator complex by increasing its reliability and efficiency and, reducing losses with a few modest upgrades to existing accelerators. These upgrades to the Booster and downstream accelerators will increase the beam power to the NOvA long baseline neutrino experiment while providing increased beam power to multiple HEP experiments.

Understanding, monitoring and controlling the beam properties of the injected beam from the current LINAC is an essential part of the upgrades. The beam injection capture and acceleration efficiency in the Booster depends very much on the quality of the LINAC beam. The Booster is a rapid cycling synchrotron which accelerates the beam on a 15 Hz sinusoidal magnetic ramp. The longitudinal acceptance of the Booster is ~5.4 MeV. The jitter in the ramp of main Booster dipole magnet power supplies during injection introduces an error of ~ 0.2 MeV. Also, there are many indications of observed energy variation from head of a long LINAC beam pulse to that of the tail. So, careful attention should be given to the energy error and energy spread of the injected beam and effort should be made to mitigate the energy error.

In the past we have measured the beam energy spread using the "notch method" [4] where a small notch of known width is created in the injected beam. The energy spread is measured by measuring the time required for beam shear and length of beam shear (in time). Although the technique gave us a reliable measurement on the energy spread of the accumulated injected beam, there are two issues which complicate the measurement procedure. In the first place this method was destructive and cannot be used on operational cycles and secondly, it was necessary to turn off the main RF system to get a clear wall current monitor (WCM) signal without RF modulation. In this paper we present an alternative method to measure the energy spread for the LINAC beam which is based on similar physics principle explained in ref. [4].

MEASUREMENTS AND DATA ANALYSIS

During early 2017 a LASER chopper system [5] is brought into operation to mitigate the beam loss in the Booster by producing notches in the LINAC pulse which are synchronized with the revolution period of the beam in the Booster. Each notch is produced by neutralizing about sixteen H^- 201 MHz beam bunch downstream of the 750 keV RFQ. Currently, one can produce up to about 18 notches in the LINAC beam pulse. As beam is stacked in the Booster by multi-turn injection, these notches lineup producing a net gap of ~ 80 ns in the Booster beam. We took advantage of this LASER chopper system and carried out research on energy spread measurements of the injected LINAC beam by two slightly different ways which are complementary to one another. The Booster RF system has little effect on the measured energy spread.

In the first method, we remove all 201 MHz bunches in the notch except one in the middle of the notch. The subsequent notches were left untouched. As this beam arrives at the Booster the single bunch in the notch will be undisturbed. One can observe turn-by-turn bunch length increase as the beam circulates in the Booster. The energy

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
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spread of the LINAC beam ΔE is related to the width W of the line-charge distribution of the beam bunch by,

$$\Delta E = \frac{\beta^2 E_s}{|\eta|}\left[\frac{W_{turn2} - W_{turn1}}{T_{Rev}}\right] \quad (1)$$

The quantities β, E_s, T_{Rev} and η are relativistic velocity, synchronous energy of the beam, revolution period of the beam in the Booster (~2.217 µs) and Booster slip factor (~ -0.4582) at the injection kinetic energy of 400 MeV, respectively. W_{turn1} is the width of the beam bunch at injection and W_{turn2} is the width of the beam bunch after one turn.

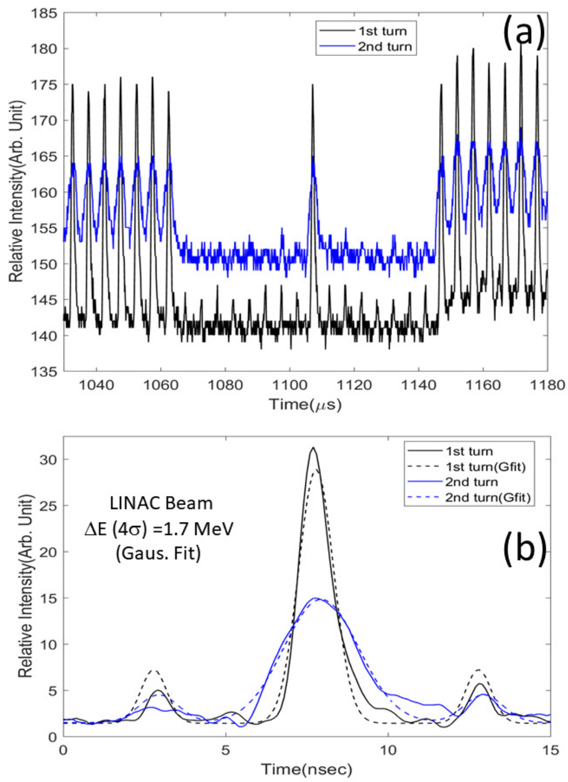

Figure 1: (a) Bunch profiles for 1st and 2nd turn in the Booster and (b) Gaussian fit to the untouched single bunch in the notch for 1st and 2nd turn. Measured ΔE are also shown.

Second method demands the length of the LINAC beam pulse to be less than about $1.9T_{Rev}$. Thus, there will be some region of the Booster beam with no overlapping 201 MHz LINAC bunches during second turn. The notch is used as a revolution reference marker during data analyses and use time evolution of those unaffected bunches for ΔE measurements.

To measure the line-charge distribution of the circulating beam in the Booster, a 6 GHz bandwidth wall current monitor (WCM) [6] is used. A Tektronix, TDS7154B Digital Phosphor Oscilloscope of type 1.5GHz 20GS/s is used to record the WCM data in combination with an ACNET application program [7].

Figure 1(a) depicts WCM data for notch region for two consecutive turns for the circulating beam immediately after injection. The notching efficiency of the laser system was only about 90% during these measurements. Consequently, we see some small amount of the beam leftover at every 201 MHz bunch region in the notch. However, the bunch length growth from 1st trace to the second trace can be seen clearly.

Figure 1(b) shows 3-Gaussian fit to the central bunch including two adjacent bunches. We normalize the second turn data to the first turn data to eliminate any beam intensity bias on the measured bunch width. The 4σ widths are extracted for both traces and we find the ΔE =1.7±0.2 MeV using the Eq. (1). We also measure $W(95\%)$ which spans 95% of the area of the central bunch and estimate ΔE =1.5±0.2 MeV.

Figure 2 shows a typical case for the 2nd method for 1st and 2nd turns with multi-Gaussian fit. In this case we have fit all shown eight LINAC bunches with one value of σ and obtain an average $\langle \Delta E \rangle = 1.9$ ±0.2 MeV.

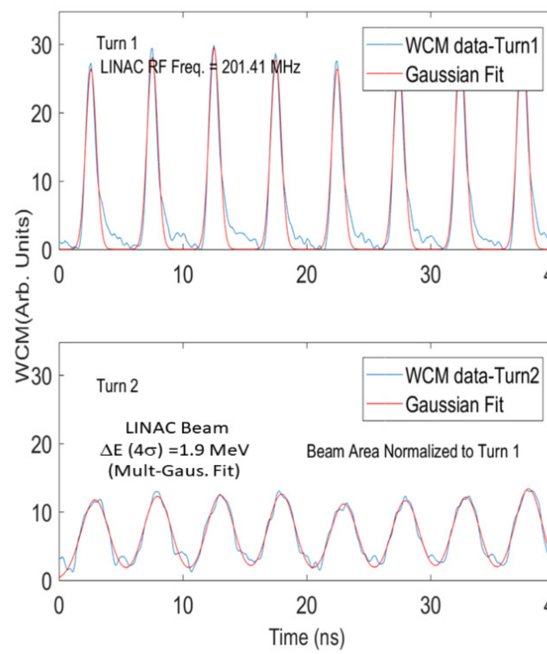

Figure 2: (a) Bunch profiles for 1st turn in the Booster and (b) multi-Gaussian fit for WCM data for the same beam on second turn. These arbitrarily chosen eight bunches with no overlapping bunches. Measured ΔE are also shown.

The illustration in Fig. 1 and 2 are for the same LINAC beam pulse; in Fig. 1 we focus on notch region of the circulating beam in Booster while on Fig. 2 our focus is on non-overlapping region of LINAC beam pulse. These data show that within the uncertainty of the measurements the measured beam energy spread compare well.

Since early 2018 we have measured the beam energy spread using this technique a number of times. The average value of the measured energy spread of the LINAC beam is 2.0 ±0.2 MeV. We find there is noticeable discrepancy

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between the previously published value of $\langle \Delta E \rangle = 1.25 \pm 0.20$ MeV [4, 8] and recent measurements. One plausible explanation for this large difference is a recent LINAC modulator upgrade to MARX modulator. So, we will investigate this issue in future.

SUMMARY

We have presented a method to measure LINAC beam energy spread using LASER notcher system. We have presented the results from two slightly different methods. Within the uncertainty of the measurements the results agree quite well.

One of the advantages of the first method is, it can be used to measure beam energy spread distribution along a long LINAC beam pulse by leaving one or two bunches in the middle of every 2nd or 3rd notch.

ACKNOWLEDGEMENTS

Authors would like to thank T. Johnson, R. Santucci, D. Slimmer for their involvement in LASER notcher system, W. Pellico, K. Seiya, C.Y. Tan, S. Chaurize, K.Triplett, and T. Sullivan for many useful discussions. Special thanks are due to accelerator operation crew for their help during our beam studies.

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