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LINAC Longitudinal Simulation and Measurement of Output Energy

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Abstract

The Linac at Fermilab, one of the oldest accelerators on-site, plays a crucial role in delivering 400 MeV proton beams to other accelerating facilities. The beam traveling through Linac needs to be carefully monitored for better accelerator operation. One of the key factors of efficient Linac operation is its longitudinal stability. The stability can minimize Linac loss and maximize beam current. For this purpose, the examination of the beam's longitudinal profile was performed, which is crucial for proper beam transfer between its two sections. After careful monitoring of the beam through Linac, we need to ensure that it leaves with desired parameters. The beam coming out from the Linac is subsequently injected into the Booster, a synchrotron that relies on dipole magnets to bend the beam at injection. If the output energy of the beam deviates from the expected value, the beam will bend at an incorrect radius, leading to potential beam loss. Therefore, precise regulation of the output energy is critical for the efficient operation of the accelerator. To address this, we have conducted a thorough examination of the Linac longitudinal simulations and data from Beam Position Monitors (BPMs). Our objective is to measure and stabilize the output energy and verify its correspondence with the predicted simulation results. All these analyses are important for efficient operation of the accelerator.

Background

The Linac is composed of two sections: the Drift Tube Linac (DTL) and the Side-Coupled Linac (SCL). The Drift Tube Linac (DTL) accelerates the beam from 750 KeV to 116 MeV and is known as low energy Linac, resonating at a frequency of 201.25 MHz. The Side-Coupled Linac (SCL) further accelerates the beam up to 401.5 MeV and is referred to as the high energy Linac, operating at a frequency of 805 MHz.

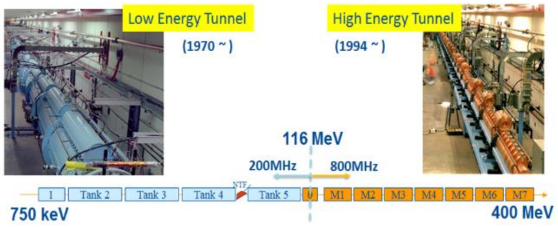

Figure 1:Linac Structure

Between low energy and high energy Linac, there is transition section which consists of two side coupled cavities, Vernier and Buncher. They do not give net acceleration, but affect the bunch length, ensuring that it will make smooth transition from low energy Linac to high energy Linac.

After leaving the Linac beam enters a transfer line which is known as 400MeV transfer line before being injected into Booster. The Booster is a synchrotron that accelerates protons to 8 GeV. Because beam needs to be injected into correct orbit into Booster, ensuring the correct output energy is essential to minimize beam loss and maintain efficient operation of the acceleration complex.

To monitor the beam energy and transverse trajectory, multiple Beam Position Monitors (BPMs) are installed in the 400 MeV transfer area.

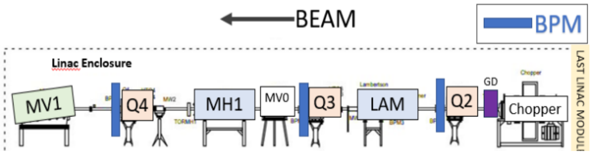

Figure 2: 400MeV Transfer line

These BPMs provide two types of data: the transverse position of the beam (horizontal and vertical) and the longitudinal phase of the beam relative to the RF reference. This data is used to calculate the output energy of the Linac, allowing for necessary phase corrections to be applied to the final RF cavity to control that energy.

Additionally, to maximize beam current through the Linac we need to ensure good matching between DTL and SCL. We monitor the longitudinal profile of the beam using a Bunch Length Detector (BLD) to ensure it aligns with our predictions and simulations. Bunch Length Detector is in the transition section between DTL and SCL. Comprehensive monitoring and regulation are vital for maintaining the efficiency and accuracy of the entire acceleration complex.

Beam Propagation Through Linac

Linac accelerates the beam with RF cavities. The RF field inside cavities is a standing wave. The RF cavities are specifically designed to create a longitudinal electric field (in the direction of beam travel). Inside the Linac there are specific structures that guarantee that the beam only sees the correct direction of electric field. Thus, every accelerating cell beam receives an accelerating "kick" from the RF field. One important concept is the synchronous particle. The synchronous particle receives the designed acceleration at every cell. For the Linac, the design cavity phase is -32 degrees. The synchronous particle will pass through every cell in the same phase with respect to the RF field modulo 360 degrees. We refer to distribution of particle energy and phase as a phase space.

Longitudinal motion of particles through the Linac can be simulated as the combined effect of series of accelerating cells. For the Fermilab Linac an in-house code exists that does that. The Linac simulation tracks the phase space of the beam as it passes through each cell of the accelerating cavities. The equations 1 and 2 represent the simplified energy gain of a particle traversing on axis.

$$E_{n+1} = E_n + eV\sin(\varphi_n) \quad (1)$$

$$(Es)_{n+1} = (Es)_n + eV\sin(\varphi_s) \quad (2)$$

In figure 3, we see the initial distribution of the Δφ and ΔE. To generate the initial distribution, the phase range is given 20 deg, the energy range is given 0.001e6 eV and 100 particles are generated. In figure 4, we observe the phase space when the bunch passes the last cell of DTL. In figure 5, the phase space of the bunch is plotted, when it passes the last cell of the SCL.

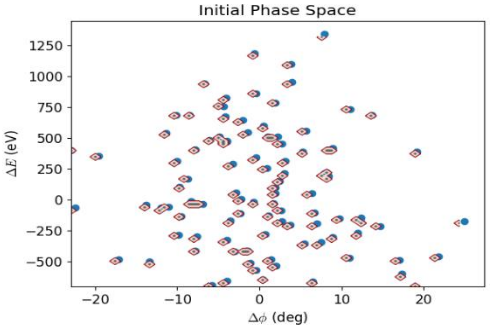

Figure 3:Initial Phase Space of the Bunch

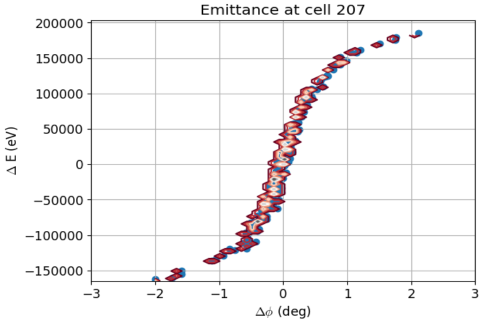

Figure 4:Phase Space after passing accelerating cell 207

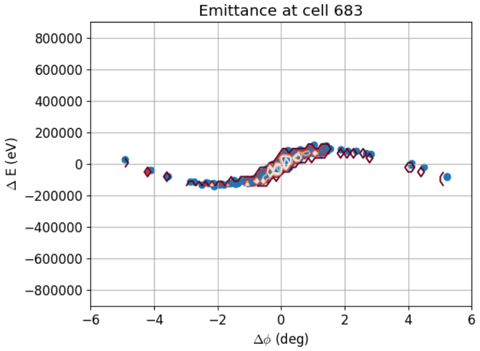

Figure 5: Phase Space after last accelerating cell

The longitudinal profile is defined as the projection of the phase space onto the phase axis. For the beam that has initial Gaussian distribution and fits within acceptance of accelerating machines, the longitudinal profile is expected to be Gaussian. If the initial distribution is bigger than the machine acceptance beam distribution will start getting distorted and we will no longer be gaussian(filamentation) as it propagates through the machine.

Beam Longitudinal Profile Simulation and Measurements

The longitudinal profile of the beam represents the projection of the phase space onto the phase axis, illustrating how the beam is distributed across phase differences. To analyze this, the longitudinal simulation was used to generate a particle beam with specific initial parameters and then track the phase space as the beam passed through each cell. After simulating the beam's passage through the last cells, we examined the resulting longitudinal profile. In figure 6, the longitudinal profile closely resembles Gaussian distribution.

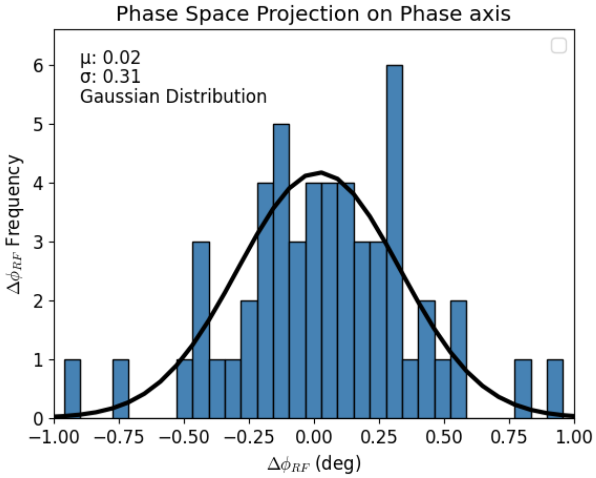

Figure 6: The longitudinal profile from simulation.

After that, we analyzed real data from the Bunch Length Detector (BLD) to examine the longitudinal profile of the beam. As mentioned earlier, the BLD is in the transition section between the low-energy Linac and the high-energy Linac. This component is crucial for assessing how well the beam exiting the low-energy Linac aligns with the high-energy Linac, given the differences in resonance frequency between the two sections. Figure 7 shows a Gaussian distribution in the longitudinal profile, indicating that the beam behaves as expected.

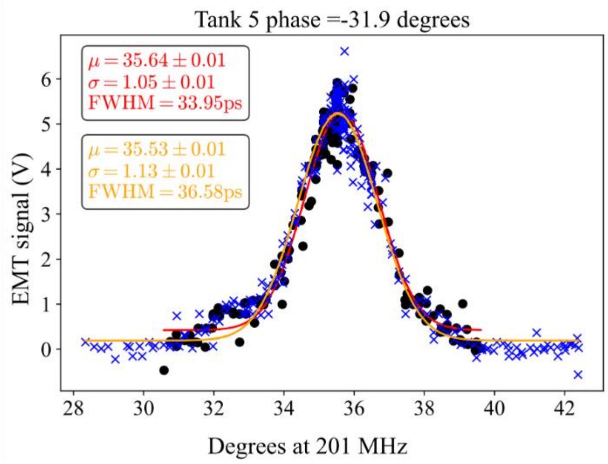

Figure 7: The longitudinal profile from BLD as a function of the last DTL cavity.

We also studied correlation between the Tank 5 phase and the bunch length, by changing the phase setting of Tank 5. Figure 8 shows the relationship between the bunch length and Tank 5 phase. The bunch length is important, because DTL and SCL operate in different resonance.

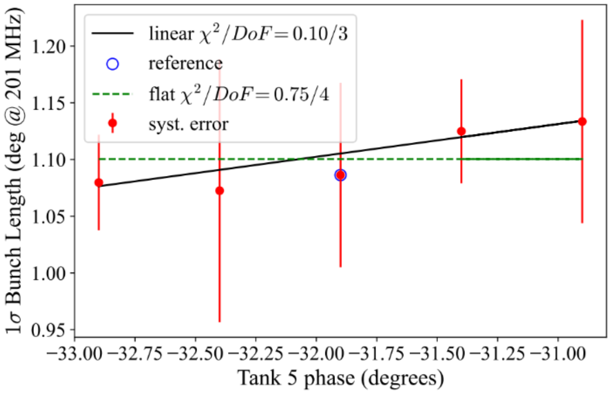

Figure 8: Bunch Length vs Tank 5 Phase

Another interesting investigation was the relationship between the mean of our obtained distribution from BLD and the RF phase of Tank 5. We can see from figure 9, that they are connected linearly, and by changing the phase we can shift the pick of our distribution.

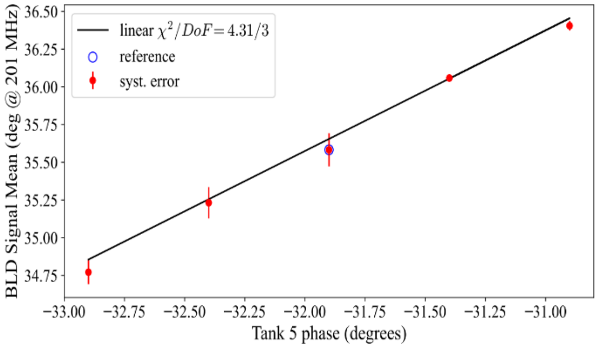

Figure 9: Pick shift as a function of Tank 5 Phase

Methods for Energy Calculations

To determine the output energy, we collected data from three BPMs in the 400 MeV transition section. As previously mentioned, BPMs provide two types of data: transverse position (horizontal and vertical) and longitudinal phase. We collected data as a function of the last Lianc RF cavity phase setting, because the cavity phase results in a change in beam energy. We utilized two methods for calculating the output energy based on this data.

During acceleration, off-momentum particles experience betatron oscillations that cause them to follow trajectories different from that of the synchronous particle. High-momentum particles are bent less by the magnetic field, while low-momentum particles undergo greater bending. This transverse deviation from the ideal trajectory, caused by momentum spread, is known as dispersion. There exists a correlation between the transverse position of the particles in disperse region and its momentum as shown in equation 3.

$$\Delta x = D(s)\frac{\Delta p}{p} \quad (3)$$

By using this relationship and data from the BPMs, we calculated the output energy of the beam. After performing the calculations, we plotted the energy data obtained from the BPMs alongside the predicted energy from the simulation. Figure 10 illustrates the measured energy data and the best fitting curve from my simulation. Through this fitted curve, we can understand the functional relation between output energy and the phase setting of the last RF cavity.

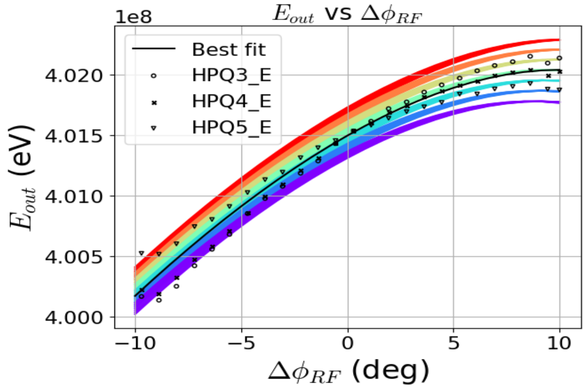

Figure 10: The output energy as a function of last RF cavity phase setting. The graph illustrates the measured energy from BPMs as well as the calculated energy from simulation.

The second method relies on time-of-flight measurement. We estimate the beam energy using the time it takes to travel between two BPMs. We use the BPM at Q2 location as a reference, as the distances between this BPM and the others are precisely known. By calculating the longitudinal phase difference between BPMs, we can determine the time it takes for the beam to travel from one BPM to another. With both the distance and time known, we can then calculate the beam's velocity and kinetic energy. Several critical factors must be considered when performing these calculations. The first challenge is calibration offset coming from the different cable lengths (signal paths) of BPMs which, if not accounted for, can lead to out-of-range results. As the BPMs measure relative phase in the range of (-180 deg, 180deg), there is an undetermined factor of 360n (where n is a whole number) when trying to determine the absolute beam phase (total time of flight). By carefully addressing these issues, we calculated the beam's output energy using the time of the flight method. Figure 11 shows the measured energy from BPMs calculated by time-of-flight method, as well as the best fitting curve for the data.

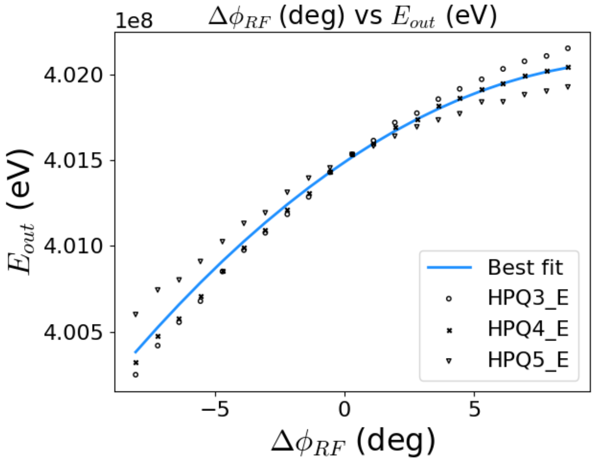

Figure 11: The output energy calculated with ToF method. The blue curve is the best fitting curve for my data.

These two calculations helped me understand the relationship between the phase change in the last RF cavity and the output energy. By applying the best fit, we can predict how adjustments in the final RF cavity will impact the beam's energy.

Cavity Phasing Measurement

In addition to tuning the machines for optimal beam quality, it is crucial to ensure that our devices operate as designed. One key aspect of proper acceleration is the design resonance of the cavity. The design resonance ensures that the synchronous particles receive correct RF kick (correct acceleration). However, due to environmental fluctuations cavity resonance can drift even at constant setting. To ensure resonance is at design, we employ a cavity phasing procedure. We measured the response on beam phase to scanning cavity phase of the Vernier cavity in transition section. Because of its small length, Vernier should operate as a thin lens. Figures 12, 13 show the beam phase change from the BPMs located at the end of SCL Module 1 Submodule 1 and SCL Module 1 Submodule 2 as a function of the Vernier RF phase setting. By fitting the data with a sinusoidal curve, we can confirm that the cavity behaves as thin lens, with the sinusoidal shape verifying the accuracy of its performance.

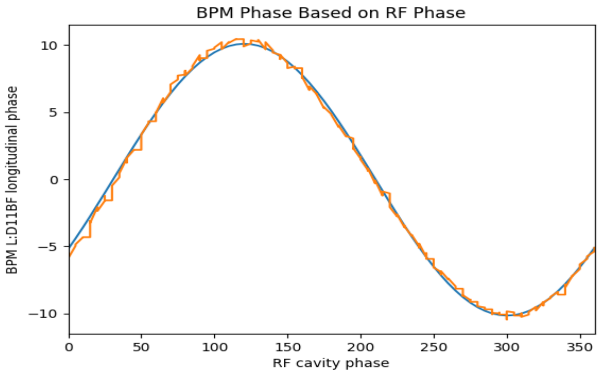

Figure12 BPM L: D11BF phase as a function of Vernier RF Phase

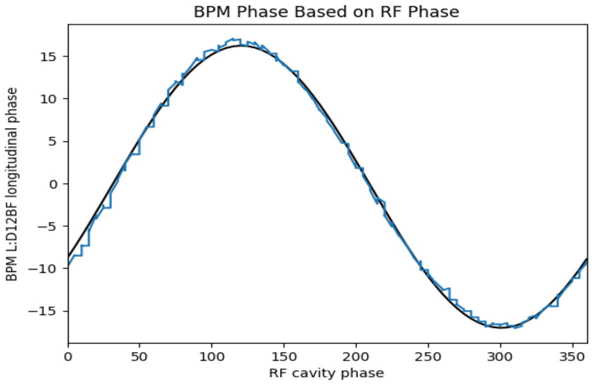

Figure 13: BPM L: D12BF phase as a function of Vernier RF Phase

Additionally, we calculated the amplitude of the sinusoidal function obtained for each BPM. As observed in figure 14, the farther the BPM is from the Vernier cavity, the greater the amplitude, and this relationship is linear. This finding further confirms that our cavities are behaving as predicted.

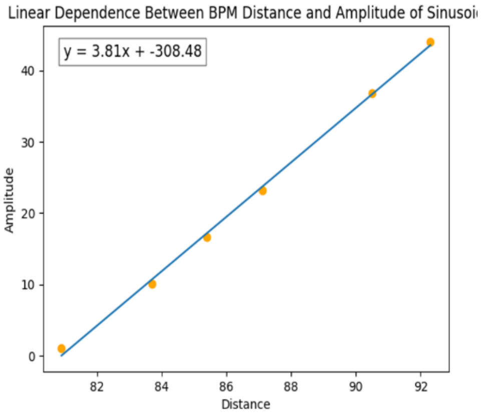

Figure 14: BPM Measured Amplitude vs BPM Distance

Conclusion

The Linac is the first machine in the Fermilab accelerator complex, responsible for delivering a proton beam to other facilities. Ensuring high-quality beam delivery requires constant monitoring and minimizing losses. The first key factor for efficient operation is the Linac’s longitudinal stability, which was examined by analyzing data from the BLD and ensuring it corresponds to design and predictions. Another important factor was the output energy, measured using two methods. These calculations allow us to understand the connection between the output energy and the last RF cavity setting. All these measurements are crucial for efficient accelerator operation and maintaining a high-quality beam.

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