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EXPERIMENTAL LONGITUDINAL EMITTANCE MANIPULATION USING LASER-BASED PHOTOIONIZATION IN THE FERMILAB LINAC*

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Abstract

A series of simulations and beam studies were conducted at Fermilab's linear accelerator to evaluate the effectiveness of longitudinal emittance control via laser-induced photoionization. While similar laser techniques have been employed at Fermilab to enhance injection and extraction efficiency into the Booster, the work presented here focuses on extending these methods to bunch-by-bunch manipulation. This approach utilizes fine-scale correction of the H- bunches' longitudinal spatial distribution. In theory, loosely confined particles in longitudinal phase space contribute to emittance growth during acceleration. By selectively removing these outlying particles through laser scraping ($H^-+\gamma \rightarrow H+e^-$), this growth can be reduced. This report presents experimental results from both symmetric and asymmetric longitudinal scraping of H^- bunches in the Fermilab linac, which were subsequently injected into Booster, and evaluates the broader applicability of this method for future high-intensity accelerator operations.

MOTIVATION

The motivation of this paper is to expand upon the results shared in previous literature [1]. Prior simulation results confirmed a 10% reduction in the longitudinal RMS emittance by photoionzing 2% of the beam halo out of the RFQ. These findings motivated an experimental investigation of energy dispersion reduction within the Fermilab Linac and Booster accelerator systems. The results shared here again utilize Fermilab's chopping system called the Laser Notcher [2]. Experimental verification of simulated models as well as novel timing techniques were investigated to explore the efficacy of energy dispersion reduction in the Fermilab Booster via laser scraping.

PHOTO-DETACHMENT FOR H$^-$ USING THE LASER NOTCHER

The Laser Notcher photo-detaches the loosely bound electron in H$^-$ to neutralize the ion's ability to accelerate [3]. The electron's photoionization cross-section is $4.2 \times 10^{-17}\ cm^2$ which is centered at a photon energy of 1.51 eV ($\lambda = 821\ nm$) in its center-of-mass frame [4]. The optimal cross section sits at a wavelength of 821 nm, but the Laser Notcher prioritizes laser amplification and uses a 1064 nm (1.165 eV) laser with a cross section of $3.66 \times 10^{-17}\ cm^2$. When characterizing the Laser Notcher's photo-detachment efficiency, it was assumed to have a high probability of interaction between photons and electrons with no depletion of photons relative to the electron detachment [4]. This allows the fractional neutralization of H$^-$ to be given by Eq. (1) [5]

$$F_{neut} = \frac{N}{N_0} = (1 - e^{-f_{CM}\sigma(E_\gamma)\tau}) \tag{1}$$

where f_{cm} is the photon flux at the interaction point in the rest frame of the H$^-$ [$\frac{Photons}{cm^2 \cdot s}$], $\sigma(E_\gamma)$ is the cross-section for a given photon energy E_γ, and τ is the interaction time of the photons and ions.

The center of mass flux may be represented in lab frame as

$$f_{cm} = \frac{E_{laser}}{A_{laser}\tau_{laser}} \frac{\lambda_{Lab}}{hc} \gamma(1 - \beta\cos(\theta)) \tag{2}$$

where $E_{laser}/A_{laser}\tau_{laser}$ is the average intensity of a gaussian laser pulse, λ_{Lab}/hc is the normalization factor for the lab frame photon energy, and $\gamma(1 - \beta\cos(\theta))$ is the relativistic Doppler shift factor.

EXPERIMENTAL VERIFICATION OF LASER SCRAPING SIMULATIONS

To verify the validity of previous laser scraping simulations, experiments were conducted to recreate the fractional neutralization found in Equation 1. This was done by attenuating the laser using an Electro-Optic Modulator (EOM). Starting from the maximum neutralization rate, with an efficiency of approximately 90%, the amplitude was attenuated to 30–90% of that initial value. The resulting data were then fit using the same modeling program described in [1].

Figure 1 shows experimental data fitted using the simulated model. The x-axis is presented in arbitrary units, as the available instrumentation could not accurately determine the pulse energy. Additional studies will be conducted to quantify the Laser Notcher energy attenuation levels. Although the exact laser pulse energy values are unavailable, a simulated fit was produced using the same modeling program described in [1].

EXPERIMENTAL LONGITUDINAL SCRAPING RESULTS

As previously stated in [1], the temporal resolution of the laser was limited by the Arbitrary Wave Generator (AWG) to 0.5 ns. As a result, the current Laser Notcher system achieves timing precision only on the order of one-quarter of

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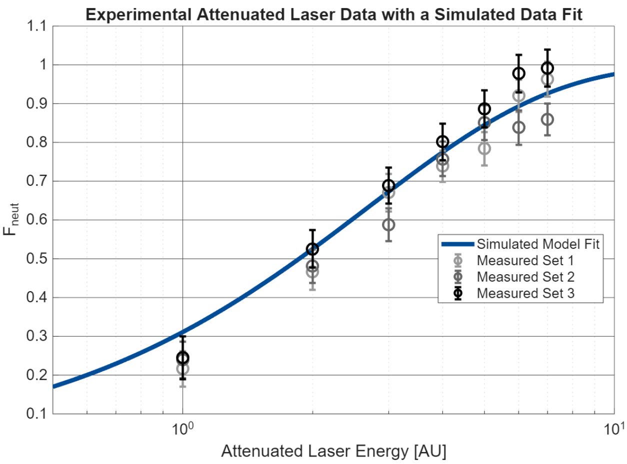


Figure 1: Attenuated laser data fitted with the simulated model.

the bunch length. Given this limitation, additional scraping techniques were investigated to optimize dispersion reduction within the Booster.

Energy Dispersion Measurement

The same approach was taken to evaluate reductions in the longitudinal halo as discussed in [1,6]. Instead of direct measurement in the Linac, the effect was assessed downstream in the Booster. This method relies on an empty notch produced by the Laser Notcher, shown in Fig. 2, and exploits the dispersion of longitudinal phase space during beam circulation. This effect manifests as a longitudinal dispersion due to the lack of longitudinal focusing from accelerating structures, as illustrated in Fig. 3.

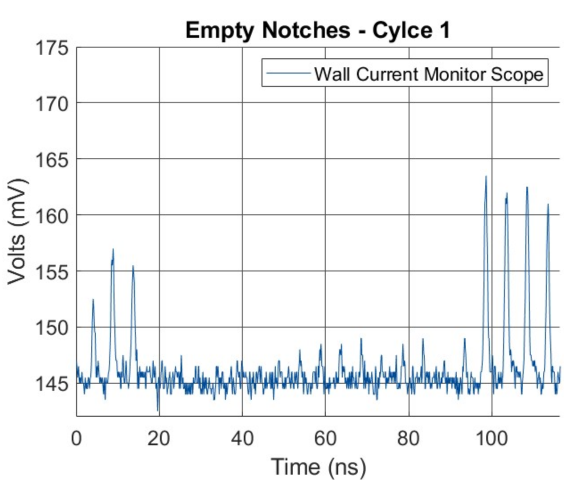
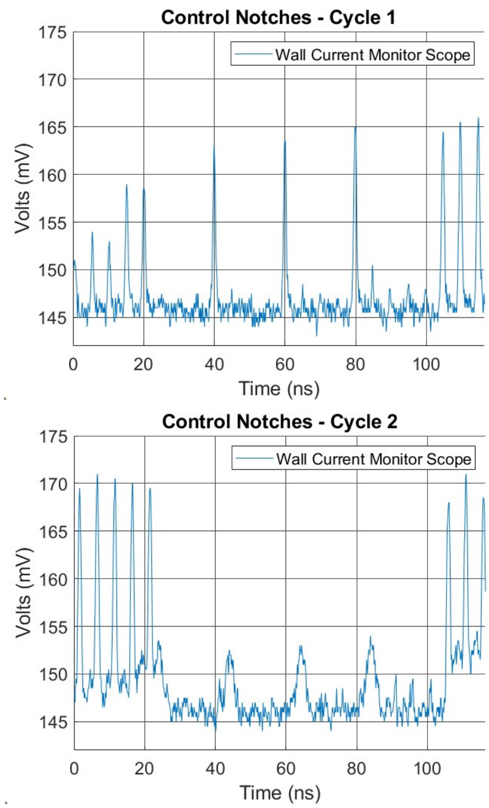


Figure 2: A Notch, formed by the Laser Notcher, measured using a Resistive Wall Current Monitor (WCM) in Sector 17 of the Fermilab Booster.

Optimizing from Previous Experiments

In [1], it was determined that Front scraping produced the greatest reduction in dispersion during the second Booster cycle and showed the largest statistical deviation from the control group. It was also found that similar scraping with symmetry however, had a detrimental effect on the energy dispersion. Due to the relatively low beam velocity, it is hypothesized that the bunch center may have interacted with the trailing edge of the second laser pulse, leading to unintended neutralization. The experiments shared in this paper investigate imparting a timing skew to symmetric laser pulses to avoid the bunches center.

[a] .



[b] .

Figure 3: (a) First Booster turn unscraped control group bunches. (b) Same group as (a), however showing the second turn in Booster and the resulting energy dispersion.

Skewed Timing Experimental Results

The scraping configurations are defined as follows: **Skewed Symmetric Short Back with Extended Front (SSSBEF)** removes the first 1 ns of the bunch and 0.5 ns after it; **Skewed Symmetric Short Back (SSSB)** removes the first 0.5 ns of the bunch and 0.5 ns after it; **Skewed Symmetric Long Back (SSLB)** shifts the back scrape by an additional 0.5 ns after the bunch and extends the front scrape forward by 0.5 ns. In total thirty bunches of each method, including the control group were collected. The resulting waveforms were fitted with Gaussian profiles, and standard deviation was used to quantify the longitudinal length in time. It should be noted that these results are preliminary and do not account for the statistical significance from the control group. Tables 1 and 2 contain the average pulse width for each scraping method and Booster turn.

By averaging the fits of all thirty bunches, it was found that **SSLBEF** produced a slight decrease in dispersion dur-

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Table 1: Average Pulse Widths for the First Booster Turn

Booster Turn One

Scrape Method	Ave. Pulse Width (ns)
Control	0.44 ± 0.10
SSSBEF	0.42 ± 0.09
SSSB	0.43 ± 0.01
SSLB	0.44 ± 0.01

Table 2: Average Pulse Widths for the Second Booster Turn

Booster Turn Two

Scrape Method	Ave. Pulse Width (ns)
Control	1.54 ± 0.01
SSSBEF	1.57 ± 0.09
SSSB	1.50 ± 0.08
SSLB	1.58 ± 0.08

ing the first turn of the Booster. In the second turn, however, it exhibited a higher energy dispersion, raising the question of whether this method could be applied to optimize the dispersion rate over multiple turns. **SSSB** showed no significant change from the first turn, but a decrease in dispersion in the second turn of the Booster. Further analysis will be conducted to evaluate the significance of each scraping configuration, with preliminary results suggesting potential emittance manipulation techniques that may be beneficial for synchrotron injection during ramping. This assertion will be further investigated with simulations using the verified laser scraping model.

FUTURE WORK

Analysis of the experimental data is still on-going, and the statistical significance of this work will be shared in future literature. Simulations of the Fermilab linac lattice are underway, and will be implemented with the most recent validated laser scraping modeling code.

CONCLUSION

Experiments were conducted to verify simulated results reported in previous literature. Laser attenuation within the Laser Notcher was found to reproduce effects consistent with those predicted by current simulated models.

Additional studies were performed to investigate the optimization of energy dispersion in the Booster. These scraping techniques were tailored to minimize unintended neutralization of the beam centroid. Experimental results indicated a reduction in energy spread during the first turn of the Booster with the **SSSBEF** configuration, and during the second turn with the **SSSB** configuration. The statistical significance of these observations will be evaluated in future work.

In conclusion, simulations continue to show promise for the development of a novel emittance manipulation technique, and efforts to achieve experimental confirmation are ongoing.

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