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DESIGN OF A NON-INVASIVE LASER-BASED BEAM PROFILE MONITOR SYSTEM FOR THE NEW FERMILAB PIP-II SUPERCONDUCTING H$^-$ LINAC*

V. Scarpine[†,1], R. Thurman-Keup[1], T. Johnson[1], D. Krokosz[1], P. Landon[2], J. Ruan[1], A. Saewert[1], R. Steinberg[1], J. Thangaraj[1]
[1]Fermi National Accelerator Laboratory, Batavia, IL, USA
[2]Boston University, Boston, MA, USA

Abstract

As part of the new Proton Improvement Plan (PIP-II), Fermilab is undertaking the development of a new 800 MeV, 2 mA H- superconducting RF linac to replace its present normal conducting 400 MeV linac. The PIP-II linac consists of a series of superconducting RF cryomodules from 2.1 MeV to 800 MeV. To limit the potential damage to the superconducting RF cavities, PIP-II will utilize non-invasive laser-based monitors (laserwires) to obtain beam profiles via photoionization. This paper will present the design of this PIP-II laserwire system including the picosecond pulsed laser, optical transport line, 13 individual laserwire stations, laser feedback and timing controls.

OVERVIEW

The PIP-II project at Fermilab is in the late stages of building a 2 mA, 800 MeV H- superconducting (SC) Linac to fuel the next generation of intensity frontier experiments [1].

Non-invasive laser-based profile monitors (laserwire) are being developed as the primary SC Linac beam profiling instruments using photoionization ($H^- + \gamma \rightarrow H^0 + e^-$) [2, 3]. PIP-II will have 13 laserwire stations from 2.1 MeV up to 800 MeV. Figure 1 shows the functional layout of the PIP-II laserwire system.

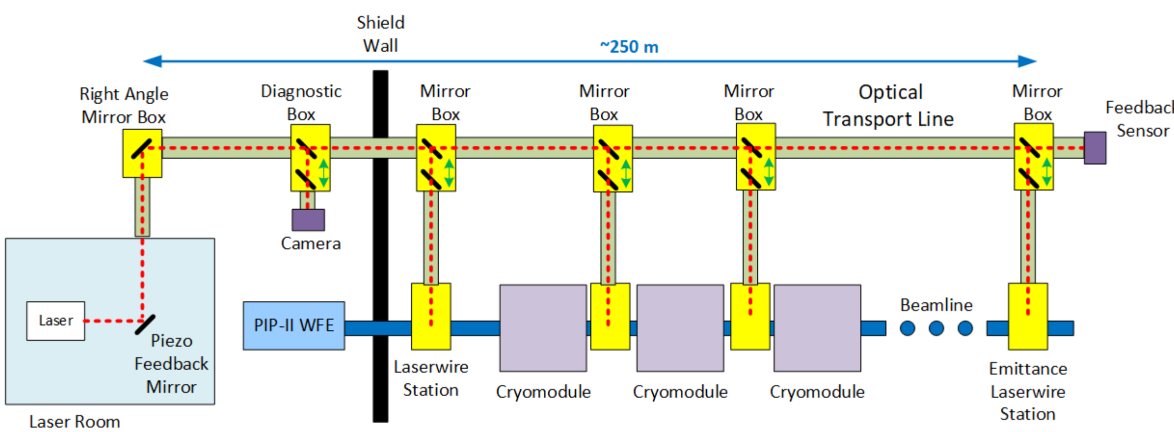

Figure 1: Functional layout of PIP-II laserwire system.

A prototype version of a laserwire profiling system based on optical fiber laser transport was tested at the PIP- II Injection Test facility (PIP2IT) [4]. This system successful measured core beam profiles but was limited by several systematic effects and proved to be impractical for a 13 station laserwire system for PIP-II. Therefore, a fiber-based laser transport system was abandoned in favor of a free-space laser transport system. A free-space transport design allows for more freedom in the choice of laser but entails the design a free-space transport system.

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† scarpine@fnal.gov

LASER TRANSPORT OPTICAL DESIGN AND FEEDBACK SYSTEM

The laser path from the laser room to the selected laserwire station will be via an evacuated free-space transport system (Fig. 1). The vacuum transport prevents air currents from distorting the laser and also serves as a safety interlock system. The laserwire system will be comprised of two lasers: a low power 532 nm CW alignment and feedback laser, and the main high power 1064 nm pulsed photoionizing laser. The low power CW laser serves two purposes. One is to aid in the alignment of the transport line, and the second is to provide a feedback signal to a piezo-controlled mirror in the laser room to adjust

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for any vibrational movement of the laser trajectory. This latter is potentially necessary as we have chosen to implement the transport without any focusing or defocusing elements to avoid accidental overfocusing on any of the beamline laserwire vacuum windows. Thus, we must keep the laser position constrained over the nearly 250 m drift length to within ~5 mm, an angular constraint of 20 microradians. Figure 2 is a schematic of the optical sections.

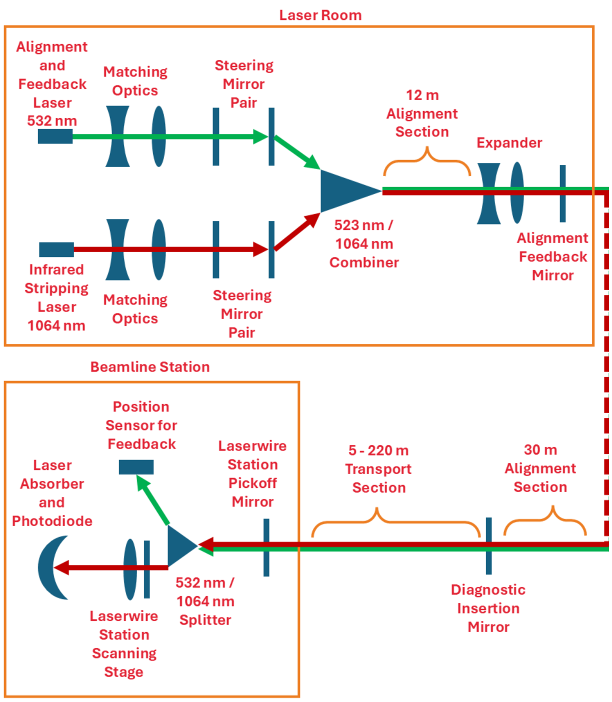

Figure 2: Optical sections for both the alignment/feedback 532 nm laser, and the H- photoionizing 1064 nm laser.

Transport

The optical design of the transport line is a free-space drift with a waist near the half-way point. Therefore, each laser begins with an optics matching section to match each lasers output optics with the desired optics of the transport line. The planned waist size in the transport is 5 mm to keep the laser spot on the vacuum windows large enough to not risk damaging them, while still being small enough to easily fit in the 100 mm diameter transport pipe. Using a simple two-lens collimation model, we studied the ability to control the optics of the transport by moving the final collimating lens. Figure 3 shows the effects of moving the lens on both the transport line and the final H- interaction point. This model indicates that movements of a few millimeters are required to make a significant change in the optics. The other result to note is that even significant changes in the laser size along the transport don't affect the focal distance at the beamline, thus virtually eliminating the possibility of accidentally focusing on a vacuum window.

To check this behavior, a simple experimental laser setup was used in a 130 m hallway. A 632 nm HeNe laser was expanded to ~6 mm rms size and collimated. Crude measurements of the spot size on graph paper were made along the length of the hallway and plotted in Fig. 4. The asymmetry between horizontal and vertical may be due to lens distortion, or the positioning of the laser through the lenses. It was not studied in depth and will be repeated with the actual expander setup in the near future.

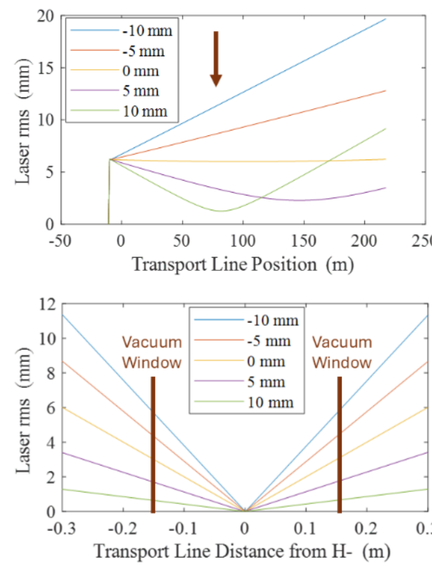

Figure 3: Laser sizes for various collimating lens positions. Top) Along the transport line. Bottom) 300 mm on either side of the H- beam at the location indicated by the arrow in the top plot.

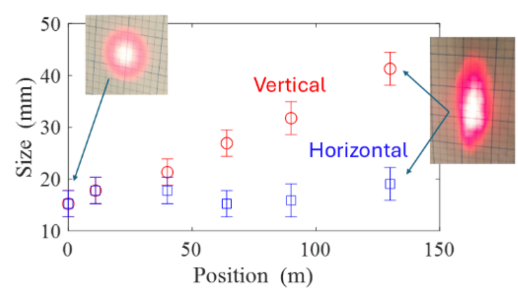

Figure 4: Experimental transport line using a 632 nm HeNe laser initially expanded to ~6 mm rms. Size axis refers to the approximate diameter of the white region of the laser spot.

Feedback

In every laserwire station, there will be a laser position sensor which will monitor the 562 nm CW laser. The sensor will be a lateral effect sensor such as the Hamamatsu S5991 which produces a horizontal and vertical position voltage value which will be sent to the laser room and used as input to the piezo-controlled feedback mirror. In addition, there will be a sensor at the end of the transport line which will serve as the feedback sensor when no laserwire pickoff mirrors are inserted.

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TIMING AND LASER PATTERN OPTIMIZATION TO MAXIMIZE SIGNAL

With small H- beam current and a non-repeating chopped beam pattern, we are optimizing the high-power laser pulses to overlap with the H- beam pulse with the following guidance:

- Laser power on vacuum windows <150 mJ/cm^2 per 10 µs up to 20 Hz
- Keep laser power per pulse in linear response region (up to ~100 µJ per pulse)
- Select laser pulse width to maximize signal (minimize wasted photons)
- Select laser pulse pattern to match chopped H- beam pattern (minimize laser power on windows)
- Laser pulse rep rate ~10 MHz over 10 µs up to 20 Hz for initial design (minimize difficult laser amplifier design)

Figure 5 shows the functional operation of the laser pattern generation. The H- beam pattern and the laserwire beam pattern timing are based on the PIP-II accelerator LCLK and is locked to the accelerator RF. The laser pattern generator then downselects the laser pulses to approximately 10 MHz.

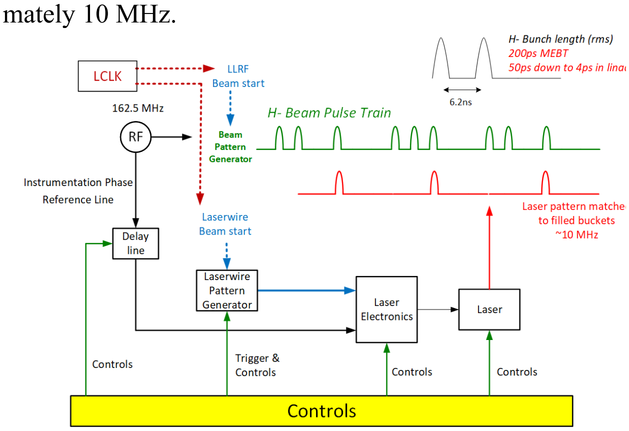

Figure 5: Functional diagram of the laser pulse pattern generation.

Laser Pulse Width Control

In order to maximize signal to noise and reduce laser power on the optical vacuum windows, the high-power laser pulse lengths will operate in the range of ~50 to 150 ps. This will allow best performance but requires stable and precise timing and electrical pulse generation. Figure 6 is a functional description of the variable laser pulse width electronics. The accelerator RF signal is split with one of the signals passing through a delay line. The signals are then recombined in a high-speed logic gate (Analog Devices HMC722LP3E) [5] to generate the short ps pulses. These pulses are then gated by a second high-speed logic gate to select the laser pattern. These electrical pulses then drive an electro-optic modulator (EOM) to create the laser pulses.

Figure 7 shows the electrical signal for the first high-speed logic gate with the top showing the input RF signals and the bottom showing the generation of a ~100 ps electrical pulse.

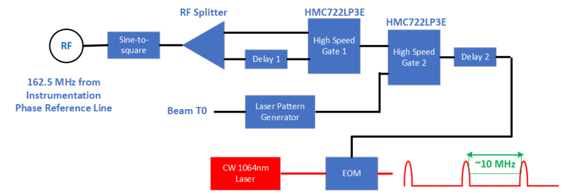

Figure 6: Functional diagram of the high-speed variable pulse length electronics. Delay 1 controls the width of the seed laser pulses. Delay 2 controls the laser pulse delay inside RF bucket. High Speed Gate 1 generates short electrical pulses at 162.5 MHz. High Speed Gate 2 selects electrical pulses that match H- beam pulse pattern.

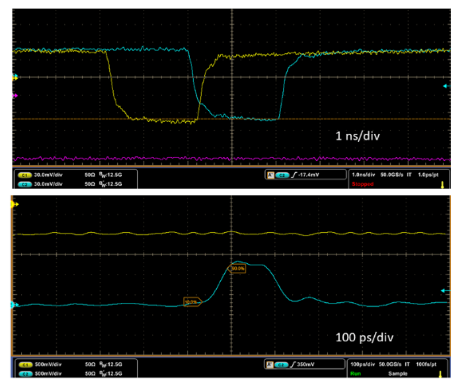

Figure 7: Short electrical pulse signal generation. Top: Phase-shifted input RF signals. Bottom: ~100 ps output pulse.

SUMMARY AND FUTURE

This paper has presented the progress on the design of the PIP-II laserwire optical transport and the short pulse laser pattern generation. We will be refining the matching and expansion optical designs as well as testing the pointing stability feedback system. We will continue the laser pattern and timing development to produce a final system. The PIP-II laserwire system will start installation in 2026 with the goal of first beam measurements in 2028.

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