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BEAM PROFILE MEASUREMENTS UTILIZING AN AMPLITUDE MODULATED PULSED FIBER LASER AT PIP2IT

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Abstract

Fermilab is undertaking the development of a new 800 MeV superconducting RF linac to replace its present normal conducting 400 MeV linac. The PIP-II linac consists of a warm front-end generating 2 mA of 2.1 MeV H- followed immediately by a series of superconducting RF cryomodules to 800 MeV. To limit the potential damage to the superconducting RF cavities, PIP-II will utilize laser-based monitors to obtain beam profiles via photoionization. This paper will present the results of transverse and longitudinal beam profile measurements using a prototype profile monitor that was tested with 2.1 MeV H- beam at the PIP-II Injector Test (PIP2IT) accelerator. This prototype profile monitor utilizes a high repetition rate fiber laser and fiber optic transport into the PIP2IT enclosure. In addition, results will be shown of narrow-band electron detection from amplitude modulated laser pulses

THE PIP-II SUPERCONDUCTING LINAC

The PIP-II project at Fermilab is building a superconducting (SC) Linac to fuel the next generation of intensity frontier experiments [1]. Capitalizing on advances in superconducting radiofrequency (SRF) technology, five families of superconducting cavities will accelerate H− ions to 800 MeV for injection into the Booster. Table 1 shows the main SC Linac beam parameters.

Table 1. PIP-II Linac Beam Parameters

Delivered Beam Energy (kinetic)	800 MeV
Particles per Pulse	6.7×10^{12}
Average Beam Current in the Pulse	2 mA
Pulse Length	550 μs
Pulse Repetition Rate	20 Hz
Bunch Pattern	Programmable

Figure 1 shows the layout of the SC Linac. The β values represent the optimal betas where the corresponding cavity delivers the maximum accelerating voltage. A room temperature (RT) section accelerates the beam to 2.1 MeV and creates the desired bunch structure for injection into the SC Linac. In the SC section of the linac, strict particle-free and high-vacuum requirement place limitation on the design and type of beam instrumentation that can be used [2]. To meet these strict particle-free conditions, invasive beam instrumentation profiling devices, such as wire scanners, are forbidden. Non-invasive laser-based profile monitors will be developed as PIP-II SC Linac beam profiling instruments. Since the PIP-II linac accelerates H- ions, laser induced photoionization ($H^- + \gamma \rightarrow H^o + e^-$) will be used to measurement beam profiles [3] in the region of PIP-II SC linac.

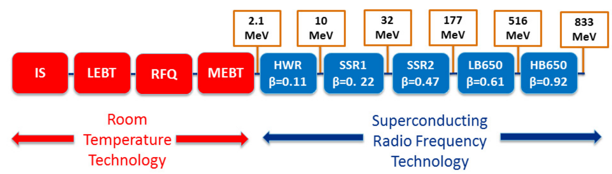

Figure 1: The PIP-II SC Linac technology map.

THE PIP-II INJECTOR TEST FACILITY

As part of the PIP-II R&D strategy, the project has developed and operated the PIP-II Injector Test (PIP2IT) facility. The PIP2IT accelerator covers the first 20 MeV of the PIP-II design [4]. The PIP2IT program performed an integrated system test of the room temperature warm front end (WFE), consisting of the ion source, LEBT, RFQ and MEBT [5], and the first two superconducting cryomodules. Figure 2 shows the layout of the PIP2IT accelerator.

The MEBT operates with 2.1 MeV H- beam up to 5 mA which includes a bunch-by-bunch chopper allowing for any arbitrary beam pattern [6]. For PIP-II beam operations, the MEBT chopper will reduce the beam current from 5 mA to 2 mA before injection into the SC linac.

To test possible laser-based profiling techniques for PIP-II, a prototype laser profile monitor was installed in the PIP2IT MEBT.

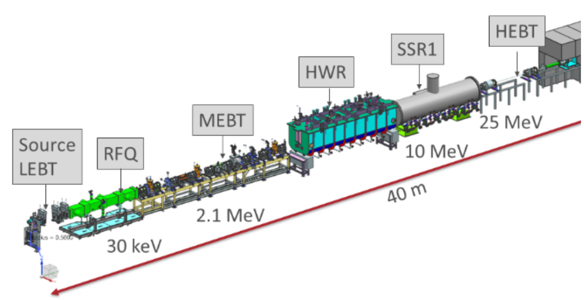

Figure 2: The beamline layout of the PIP-II Injector Test.

PROTOTYEP LASER-BASED BEAM PROFILER FOR PIP2IT

We have developed a prototype laser-based beam profiler to develop techniques that may be used at PIP-II. The prototype profile monitor is based on a low-power fiber laser with all-fiber optical transport through the linac [7]. The fiber laser is an Ytterbium seed laser with amplifier

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stages from Pritel [8] and operates at the PIP-II bunch repetition rate of 162.5 MHz. The laser light is transported into the beamline via 30m of Nufern PM1060L [9] single-mode polarizing maintaining optical fiber. The laser pulses inducing a small number of photoionization per bunch. Table 2 gives a list of the parameters of the fiber laser system. To improve the signal detection, the laser pulses may be amplitude modulated to allow detection of the photoionized electrons at the same modulation frequency using lock-in amplifier techniques.

Table 2. Fiber Laser Parameters

Laser wavelength	1054 nm
Laser power at beamline	Up to 1 W
Laser pulse frequency	162.5 MHz
Laser pulse width (fwhm)	12 ps

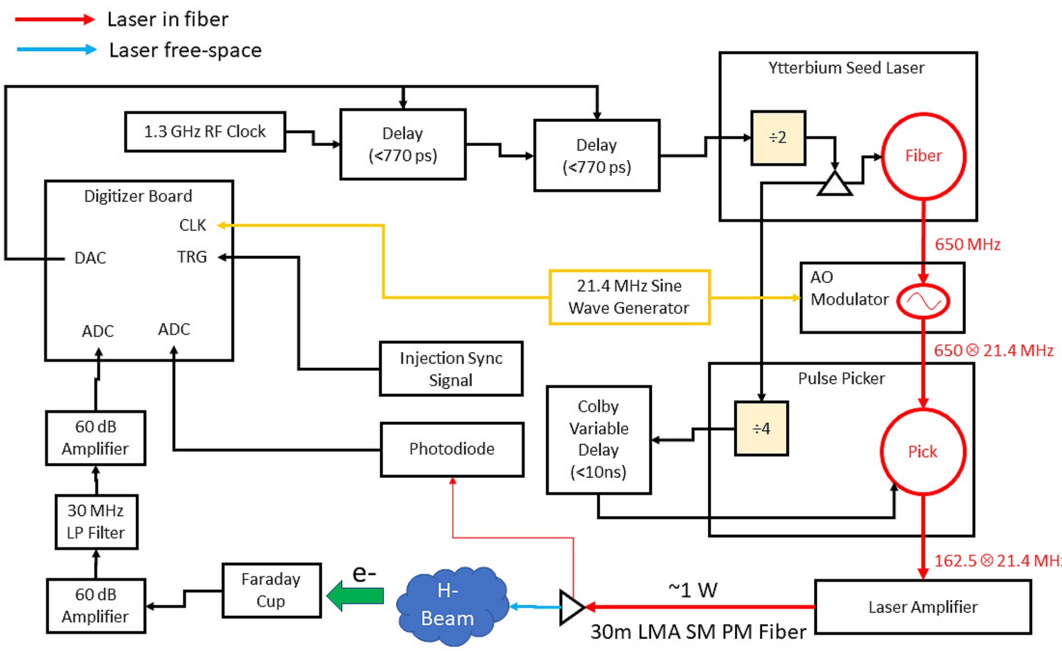

Figure 3: Block diagram of the laser profile monitor system.

Laser Profiler System

Figure 3 shows a block diagram of the laser profile monitor system. The fiber laser is locked to 8th harmonic of the accelerator RF frequency at 1.3 GHz and the laser generates pulses at 162.5 MHz. The laser pulses go through an acousto-optic (AO) modulator which amplitude modulates the laser pulse train at 21.4 MHz. The laser pulses are then amplified. The amplified laser power is limited to ~1W to limit damage to optical fibers and vacuum optical viewports. The laser system and electronics are located outside of the PIP2IT beamline enclosure, and the laser light is transported via a single-mode polarize maintaining fiber into the enclosure to the beamline vacuum chamber. The optical fiber is terminated on a collimator for free-space transport through optical vacuum viewports to the H-beam. To prevent potential damage to the viewports, the laser light is expanded and refocused on to the H- beam. The optical design limits the optical power density at the vacuum viewports to less than 3 W/cm^2. To make transverse H- beam profile measurements the laser is scanned across the beam using a linear motion stage. To make longitudinal H- beam profiles the phase of the RF signal to the laser system is changed. Figure 4 shows the layout of the free-space optics.

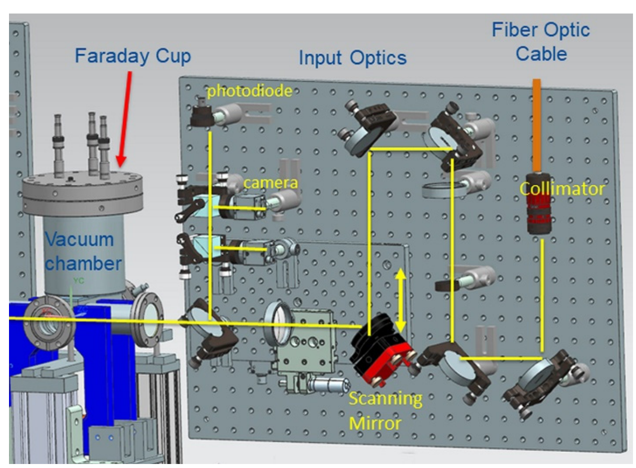

Figure 4: Block diagram of the input optics.

The electrons released from the photoionization are transport by deflection dipole magnets into a Faraday cup. Signal levels from the Faraday cup are expected to be less than a few nA. The signal is amplified by 120 db and filtered before being sampled in by 16-bit ADCs. For amplitude modulated measurements, the digitizing board is

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locked to modulating frequency. This allows signals from multiple beam pulses to be combined coherently in phase.

BEAM MEASUREMENTS

Initial beamline measurements were made without amplitude modulation of the laser pulses. This allow us to study the background electron signals in the PIP2IT MEBT that are generated by H- beam-beam striping. This effect produces background electrons that have the same kinetic energy as the photoionized electron. The laser profiler was operated with laser off and then on to get an estimate of the background. Figure 5 shows the Faraday cup signal with the laser off and then on. The data shows a 2 nA signal with the laser off and a 6 nA signal with the laser on. This large background signal limits the dynamic range of this broadband direct current profile measurement and hints that a narrowband lock-in amplifier might eliminate this incoherent background.

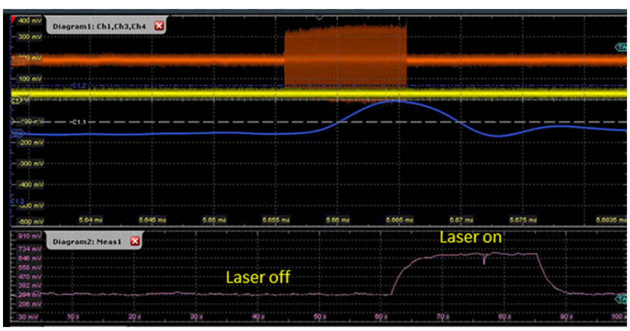

Figure 5: Faraday cup signal with the laser off and then on.

Beam Measurements without Amplitude Modulation

Longitudinal beam profile measurements were made without amplitude modulation. To make the longitudinal profile measurements the phase of the laser pulses was scanned over 360 degrees of the 162.5 MHz beam frequency. The large 120 db gain of the signal amplifiers required many beam pulses to be averaged to reduce the incoherent amplifier noise. Figure 6 shows a longitudinal profile measurement and a Gaussian fit to the data gives a 207 ps RMS bunch length, which is consistent with the expected bunch length.

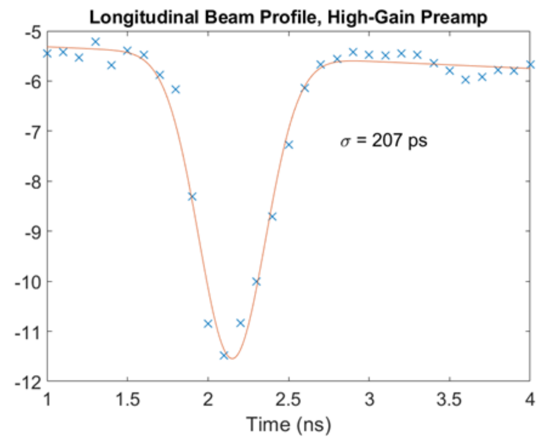

Figure 6: Longitudinal beam profile without amplitude modulation.

Beam Measurements with Amplitude Modulation

Transverse beam profile measurements were made with amplitude modulation of the laser pulses. The laser was scanned transversely across the H- beam using a linear stage. The digitizer board was locked to the 21.4 MHz amplitude modulation frequency and data from multiple beam pulses was added coherently. This allowed for a very narrow bandwidth measurement and a reduction of noise and incoherent background electrons. Figure 7 shows a transverse beam profile measurement and a Gaussian fit to the data gives a 1.8 mm RMS beam size, consistent with expected beam size.

In our initial amplitude modulation measurements at PIP2IT, the reduction in noise was limited due to crosstalk between the modulation signal to the laser and the input signal to our digitizing board. Steps to mitigate this crosstalk, such as better cables and cable layout, will be taken at PIP-II. However, this present measurement gives a proof-of-principle of the amplitude modulation technique.

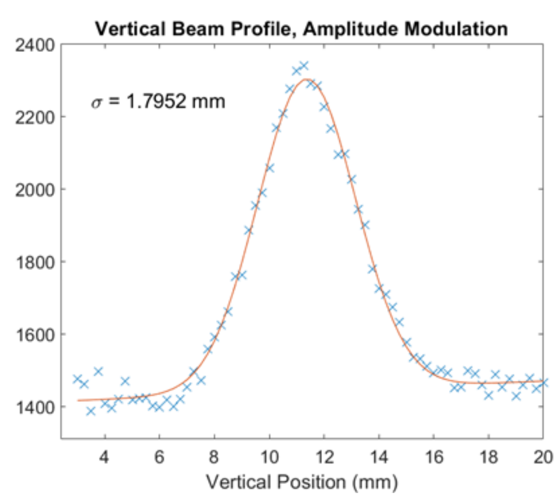

Figure 7: Transverse beam profile with amplitude modulation.

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SUMMARY

A prototype H- transverse and longitudinal beam profiler based on an amplitude modulated fiber laser source was constructed and tested at the PIP2IT accelerator. This prototype unit successful demonstrated a lock-in amp technique to make beam profiles from amplitude modulated laser pulses. In addition, locking the DAQ system to the same modulation frequency allowed the lock-in amp technique to be used for pulsed signals.

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