A LOW-POWER LASER WIRE WITH FIBER OPTIC DISTRIBUTION*

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Abstract

Laser-based position diagnostics for hydrogen ion (H-) beams typically use high power optical pulses that must be transported via free space to the diagnostic point. It is difficult to maintain stable alignment through such systems, especially when multiple channels are required. We describe a method for distributing low power, amplitude modulated pulse trains via fiber optic, and detecting interaction with the H- beam by synchronous detection of the stripped electrons. The average beam power is below one Watt. Synchronous detection at RF frequencies allows for efficient noise rejection when using optical powers below the nonlinear threshold of an optical fiber. We present results of tests of the optical system with 100m, single-mode fiber and realistic detected signal levels.

GENERAL APPROACH

Previous laser wires have used high peak power laser sources to drive the photodissociation process near saturation [1, 2]. Transport of high power pulses cannot be through fiber optic due to nonlinear effects and damage thresholds. Free space transport is therefore required, along with automatic alignment mechanisms. Due to the large number of diagnostic points required for Project X, we decided to pursue development of a fiber-delivered laser diagnostic in order to avoid construction of a free-space delivery line. Nonlinear effects in the fiber, including Raman scattering and self-phase modulation (SPM) will limit the transmitted power, so we investigated these effects experimentally and theoretically. There are different types of fiber available for the 1 micron wavelength range, some with solid core and some with hollow core. With no solid material in the core, nonlinearity is greatly reduced, but loss and dispersion are higher. Dispersion can be compensated with additional optical elements, at the cost of more loss and increased complexity at either the transmitter or the receiver. We opted to use solid core fiber for simplicity and low loss.

Project X Requirements

The development of this diagnostic is for the proposed Project X proton accelerator at Fermilab. For the current design, several general requirements were defined:

- 15 transverse diagnostics for 1-2mm beams,
- One longitudinal diagnostic for up to 100ps bunches
- ~10% resolution for normal measurements, with option for occasional measurements to 10-4 of the peak density to detect halos near the bunch

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The whole facility would span ~100m, so a fiber length of 100m was chosen as the maximum length a signal would have to travel from a central laser. Due to high radiation at the diagnostic location, the laser could not be located at the diagnostic point, even if there was a low cost laser which could be replicated for each diagnostic.

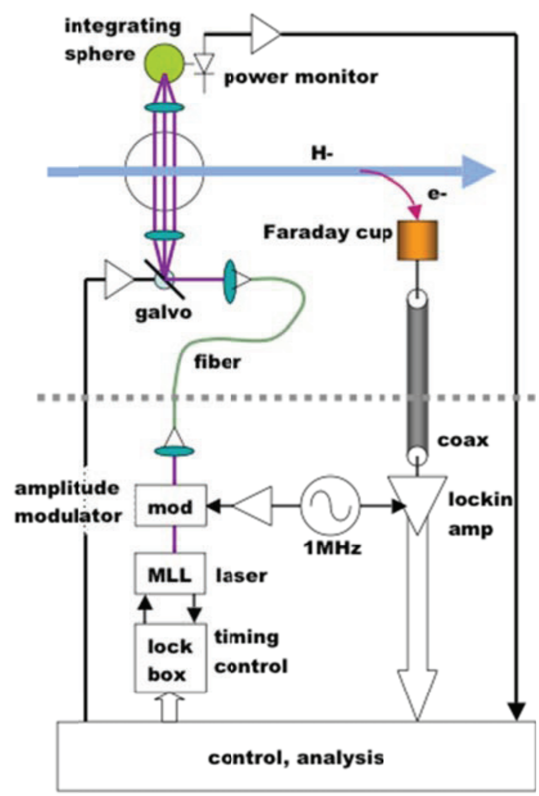

Figure 1: Laser wire block diagram.

PROPOSED LASER WIRE SCHEME

Refer to Fig. 1 for a block diagram of the proposed scheme. At a location central to the various diagnostic points, a modelocked fiber laser produces 10-100ps pulses at the microbunch rate (162.5MHz). The laser reprate is locked to an RF clock to be synchronous with the bunches. The pulse train is amplitude modulated at a frequency where noise from other processes is a minimum, arbitrarily chosen at 1MHz initially. This pulse train is then transferred to the diagnostic via fiber, where one or two galvanometer scanners move the laser beam through the bunch. The photodissociated electrons are deflected by a magnet or electric field to a Faraday cup to produce a current in a coaxial cable. A voltage thus appears at the input to the lockin amplifier, which only amplifies a small frequency range around the reference frequency of 1MHz, eliminating most noise. A low-pass filter could be added before the amplifier input. Data from the lockin amplifier are accumulated as the galvanometer scanners are controlled to scan the beam, resulting in transverse profiles. For longitudinal profiles, only the scanning process is different. The laser beam is parked at the transverse center of the bunch, and the RF clock signal delivered to the laser's reprate lock is varied in phase. This changes the arrival time of the laser pulse with respect to the bunch, and scans the bunch longitudinally.

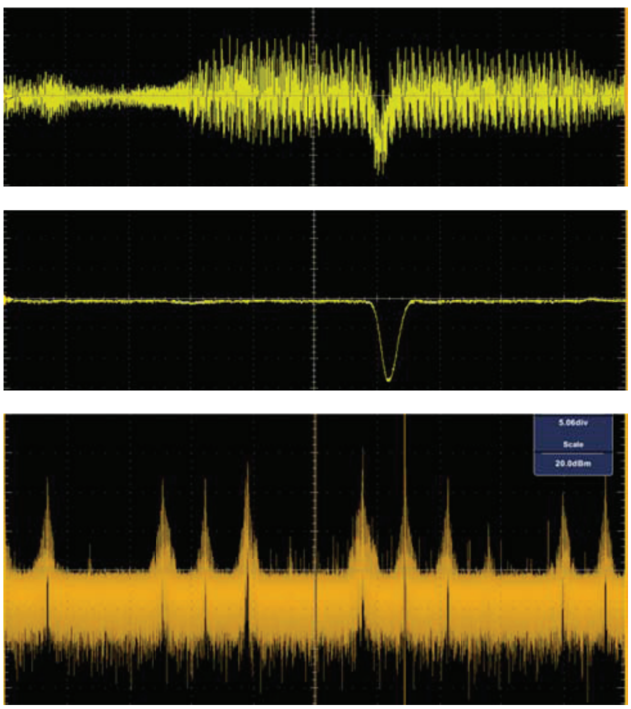

Figure 2: Noise on SNS laser wire in time domain (a), low pass filtered (b) and FFT of a 10us section of noise (c). Upper traces: 20mV/div., 100ns/div. Lower trace: 20dB/div., 125MHz/div.

MEASUREMENTS

Noise Measurements at SNS

We made measurements of the signal available from the SNS laser wire [2]. SNS applies a 10ns laser pulse to the microbunch train at 402MHz, resulting in a short duration signal (from the overlap with several microbunches) amid noise from various sources. These could include RF pickup or self-stripping of the H- beam. As shown in Fig. 2, when the signal is low-pass filtered at 20MHz, a clean signal results. Taking the FFT of the noisy signal shows that most of the noise power is above 80MHz. Though the baseline is dominated by digitizing noise, this indicates a quiet zone at lower frequencies. Further measurements with a low noise RF spectrum analyzer would give the noise power per Hertz, which would indicate if the proposed scheme will provide the needed signal-to-noise ratio.

Noise Measurements of the Lockin Amplifier

The other important noise source is the equivalent noise power at the input to the lockin, an SR844 amplifier from Stanford Research Systems. We measured this noise by observing the output of the amp with 1MHz modulated input from a photodiode, with either 1ms or 4ms pulse width, and with 100, 300 and 1000 microsecond integration time. The resulting output was recorded on a digital oscilloscope and RMS values calculated. In all cases, noise was within 30% of 4nV/rootHz, specified for this frequency band.

Nonlinear Propagation Measurements

We measured the spectral broadening of pulse trains propagated through 100m of single mode fiber with 6 micron core diameter. The optical bandwidth of the 10ps FWHM input pulse was 0.28nm on an optical spectrum analyzer with 0.01nm resolution. This bandwidth is 1.7 times the transform-limited bandwidth of 0.17nm. Measuring the output peak phase shift as the input power is increased yields the blue curve in Fig. 3.

Since the bandwidth increases with peak optical phase shift, and the phase shift is a function of peak optical power given by [3]

$$\delta\omega \cong 0.86\, \Delta\omega \phi_{\max}$$

$$\varphi_{\max} = P_0 z_{\mathrm{eff}} \frac{n_2 \omega_0}{c A_{\mathrm{eff}}}$$

where $\Delta\omega$ is the initial bandwidth, P_0 is the peak power, n_2 is the nonlinear index, and A_{eff} is the fiber core area, one could expect a linear increase of bandwidth with optical power, unless the pulse was also spreading due to dispersion. In that case, the peak optical power decreases due to an increase in pulse duration. This is predicted by the model, which was input with published values for the nonlinear index and dispersion coefficients.

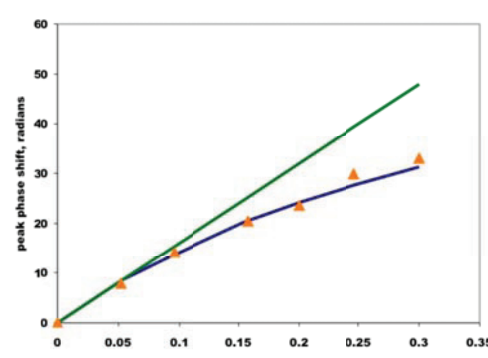

Figure 3: Peak phase shift versus transmitted power from experiment and from model.

CALCULATED PERFORMANCE

Calculated Pulse Propagation

Our model is based on transmission matrix software (OPALS). We ran the model with three input pulse widths and two fiber lengths: 1, 10 and 100ps pulses in 100 and 30m fibers (Fig. 4). 1ps pulses experienced much greater dispersion and self-phase modulation (SPM). The SPM chirp is proportional to the second derivative of the pulse envelope, so a shorter pulse has larger SPM as well as larger initial bandwidth. For 100ps pulses, there is almost no change in pulse width up to 200W. The simulation was stopped at the onset of intrapulse interference (optical wave breaking), causing the model to break down. Since this is also where the pulse develops large temporal side lobes, we made this the nonlinear limit (~250W for both 100ps, 100m and for 10ps, 30m). The threshold for Raman scattering was calculated as 600W for a 10ps pulse. Raman scattering would produce a frequency-shifted pulse arriving at the diagnostic before the H- bunch, effectively resulting in loss.

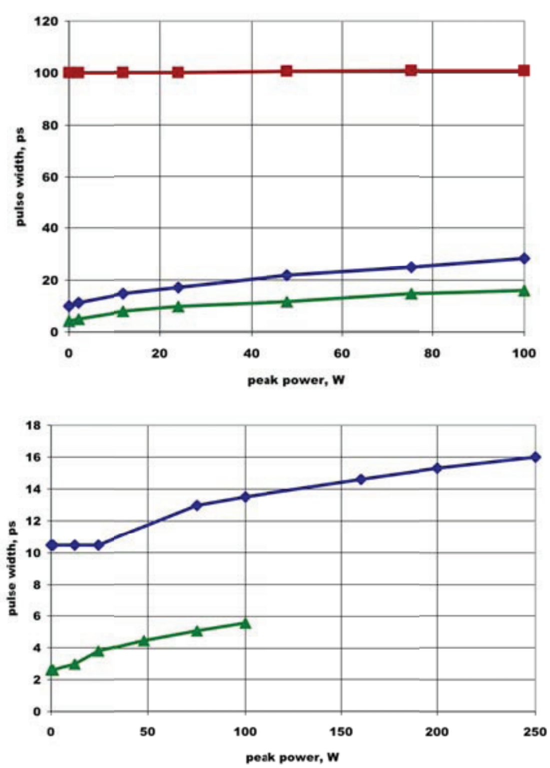

Figure 4: Model results for different pulse lengths and 100m fiber (a), 30m fiber (b), versus power.

Calculation of Signal Level

We derived the efficiency for photodissociation as a function of the H- and photon densities, and calculated the electron yield as a function of laser power for a typical Project X beam. With an H- beam of 2mm diameter, and a 1 micron wavelength laser beam ten times smaller, the voltage across a 50 Ohm load would be 1.8 microVolts per Watt. We chose 1 micron even though the cross section peaks at around 830nm, because with lower energy photons there are more per Watt. This shifts the peak yield toward longer wavelengths.

The yield was also calculated based on scaling results from the SNS laser wire. Based on Ref. 2, we derived an efficiency of ~15 microVolts per Watt, although the SNS beam parameters are different from those of Project X. Given the match between prediction and measurement in the SNS case, the physics is understood and we can use our value of 1.8 microVolts per Watt as a reasonable example.

Parameters for a Practical System

Given the predictions above, we designed two systems for transverse and longitudinal measurements. A harmonically modelocked Yb-doped fiber laser can produce pulses of 1-100ps, depending on intracavity filtering. wavelength, but that is not a concern in this application. This laser can be followed with an electro-optic modulator and a Yb-doped fiber amplifier with 5W of output power or more. Distribution of light to one of 16 outputs can be accomplished with a MEMS fiber switch capable of switching several Watts of power. Thus, all the components for a transmitting system can be high-reliability fiber devices, which would fit easily into an electronics rack.

The parameters for the two systems are summarized in Table 1.

Table 1: System Parameters

Measured	Transverse	Longitudinal
Fiber length	100m	30m
Pulse length	100ps	15ps
Peak input power	200W	200W
Reprate	162.5MHz	162.5MHz
Average power	3.3W	0.33W
Signal amplitude	6μV	6μV
Number of averages	1	100
Signal-to-noise ratio	35	35

CONCLUSIONS

We have shown that a practical H- laser profile monitor can be built using solid core, low loss fiber. We will continue to test this concept on an H- source (HINS) at Fermilab.

REFERENCES

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[2] Y. Liu, A. Aleksandrov, S. Assadi, W. Blokland, C. Deibele, W. Grice, C. Long, T. Pelaia, and A. Webster, “Laser wire beam profile monitor in the spallation neutron source (SNS) superconducting linac,” Nucl. Instr. and Meth. A 612 (2010) 241.

[3] Govind P. Agrawal, Nonlinear Fiber Optics, Academic Press, San Diego, 1995, p. 93.