LASER TIMING JITTER MEASUREMENTS AT THE FERMILAB A0 PHOTOINJECTOR

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Abstract

The Fermilab A0 Photoinjector is a 16 MeV high-intensity, low emittance electron linac used for advanced accelerator R&D. To achieve a high quality beam here it is important to maintain a stable laser in terms of both intensity and timing. This paper presents our measurement of the laser timing jitter, which is the random late or early arrival of the laser pulse. The seed laser timing jitter has been measured to be less than 200 fs, by examining the power spectrum of the signal of a fast photodiode illuminated by it. The pulsed and pumped laser timing jitter has been measured with limited resolution to be less than 1.4 ps, by examining the phase of a cavity impulsively excited by the signal from a fast photodiode illuminated by the laser pulse.

INTRODUCTION

Photoinjectors are widely used in particle accelerators. They have uses from nuclear and high energy physics research in collider experiments (e.g. ILC), to biology and condensed matter research in light source experiments (e.g. XFEL).

The A0 Photoinjector [1] consists of a 1.3 GHz copper RF gun and a TESLA type RF cavity, and is a 16 MeV high-intensity, low emittance electron linac used for advanced accelerator R&D at Fermilab.

To achieve a high quality beam for advanced accelerator R&D it is important to maintain a stable laser in terms of both intensity and timing. Timing jitter of the laser is the unwanted random variation of the pulse arrival time. Low beam timing jitter is good because it increases collider luminosity (e.g. ILC nominal: 0.5ps RMS), and is necessary for Lasing in FEL (e.g. XFEL: 0.1ps RMS).

The laser timing jitter has been measured by examining the power spectrum of the seed laser at the 12th harmonic, and by examining the phase of a cavity impulsively excited by the signal of a fast photodiode illuminated by the pulsed laser shot. Our aim is to have a pulsed laser timing jitter measurement resolution of less than 200 fs.

A0 LASER SYSTEM OVERVIEW

The A0 Laser System (Fig. 1) [2] consists of a seed laser, pumps, and two sets of doubling crystals. The laser begins as a continuous train having 5.5 nJ per FWHM 5 ps long infrared (1054 nm) laser pulses at 81.25 MHz. Some pulses (10 to 10000 out of 81.25 million) are allowed to pass through every second, to be pumped by a series of amplifiers. The amplified laser then passes through two sets of doubling crystals to become first green, then ultraviolet (UV). This UV laser having 5 μJ per FWHM 5 ps long pulse is directed with only three turning corners to hit the Cs_2Te photocathode to generate 10 nC of electrons per pulse to be accelerated to 16 MeV.

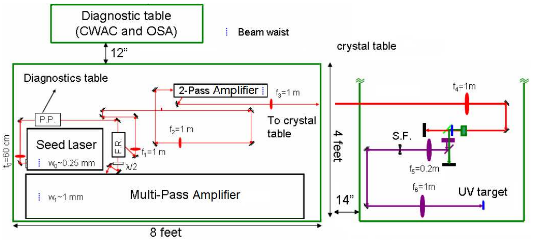

Figure 1: Layout of the A0 Laser System.

SEED LASER TIMING JITTER

To study the laser timing jitter we begin at the seed laser (Time Bandwidth Products GE-100), which gives a continuous train having 5.5 nJ per FWHM 5 ps long infrared (1054 nm) laser pulses at 81.25 MHz. A high-speed photodiode with a rise/fall time of 12 ps (Fermionics Lasertech HSD-30) is illuminated by the seed laser, and the electrical output signal from the photodiode is analysed by a microwave spectrum analyzer (Agilent E4445A).

The power spectrum of the photodiode signal contains information both on the amplitude and timing jitter. The technique of calculating the timing jitter from the power spectrum is called the Power Spectral Density Technique. Amplitude jitter and timing jitter both show up as shoulders beside the spectral lines (Fig. 2). The RMS jitter is given by an integral of the power in the shoulders (Eq. (1)):

$$\text{RMS Jitter}_{\,f_1 to f_2} = \frac{1}{2\pi f_c}\sqrt{2\int_{f_1}^{f_2} 10^{\frac{L(f)}{10}}\,df} \qquad (1)$$

Where the factor of 2 inside the square root uses the fact that the spectral shoulders are symmetric.

To separate the amplitude and timing jitter, we make use of the fact that amplitude jitter shoulder is constant, whereas the timing jitter shoulder is proportional to the square of the frequency [3], and measure the power spectrum of the 12th harmonic of the 81.25 MHz pulse rep rate. The timing jitter is measured to be 184 fs at 10 Hz to 10 kHz (Fig. 3).

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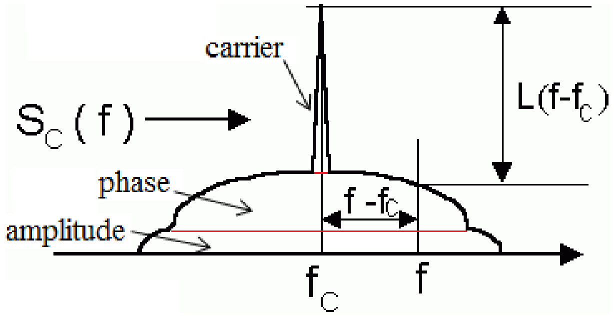

Figure 2: Sketch of a spectral line showing phase and amplitude shoulders.

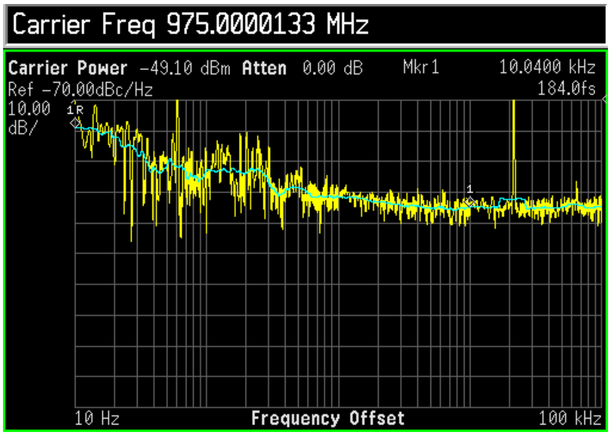

Figure 3: Timing jitter integral taken at 12th harmonic (975 MHz) from 10 Hz to 10 kHz gives 184 fs.

Seed Laser Timing Jitter Resolution

To study the resolution of our application of the Power Spectral Density Technique, we measure the phase noise of the 1.3 GHz Master Oscillator (MO). The MO is the reference of our "Timing Distribution System", which has a very low jitter. Our resolution is 88 fs since the spectrum analyzer has an 88 fs jitter with respect to the MO (Fig. 4).

PULSED LASER TIMING JITTER

Next we study the timing jitter of the pumped laser, which gives one train per second, consisting of 10 to 10000 infrared (1054 nm) pulses spaced by 1 μs, having 6 μJ per pulse. This laser is attenuated to 1/1000 the original amplitude, then directed to illuminate the high-speed photodiode with a rise/fall time of 12 ps (Fermionics Lasertech HSD-30). The electrical output pulse from the photodiode is fed through a band pass cavity filter with a Q of 2600 and tuned to a center frequency at 1.28 GHz (EMR Corp. 6754/SBC). The photodiode causes the cavity to start oscillating (ringing) at a frequency of 1.28 GHz, which decays slowly (cavity energy reduces by 96% in 2600 oscillations). The phase of the ringing is measured to infer the timing of the laser pulse. We call this technique of measuring the phase of the ringing of the filter to get timing information the Ringing Filter Technique (Fig. 5).

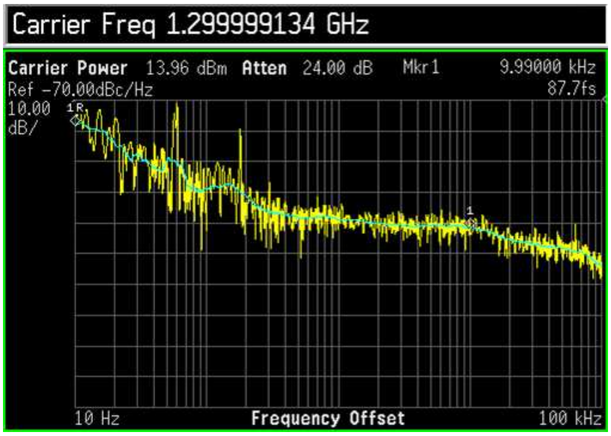

Figure 4: Timing jitter integral of the MO taken from 10 Hz to 10 kHz gives 88 fs. This is the resolution of our application of the Power Spectral Density Technique.

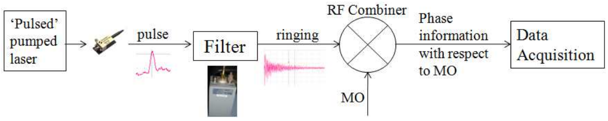

Figure 5: Sketch showing our application of the Ringing Filter Technique.

To measure the phase of the ringing we first feed it through an RF amplifier (ZHL-1042J), then superimpose it onto the 1.3 GHz Master Oscillator signal with an RF Combiner (RF Splitter Mini-Circuits ZX10-2-25, used in reverse). This superimposed signal is recorded by an oscilloscope (LeCroy Wavepro 7200A) using a single channel (avoiding the relative jitter between 2 channels). The superimposed signal has two main frequency components, 1.28 GHz (the cavity filter ringing) and 1.3 GHz (the MO reference) (Fig. 6). With an FFT done on the oscilloscope, one can find the phase of both the cavity ringing and the MO reference (Fig. 7).

The phases of the ringing and the MO are both dependent on the time which the oscilloscope has triggered, but the relative timing difference between them is not. The relative timing difference of each run modulo 770 ps (period of 1.3 GHz MO) is given by Eq. (2):

$$\Delta T_{filter} = \frac{\phi_{filter}}{\omega_{filter}} - \frac{\phi_{MO}}{\omega_{MO}} \tag{2}$$

Armed with the ΔT from 20 pulses, the RMS of this distribution gives us the pulsed laser timing jitter of 1.4 ps (Fig. 8).

Pulsed Laser Timing Jitter Resolution

To study the resolution of our application of the Ringing Filter Technique, we measure the phase noise of the

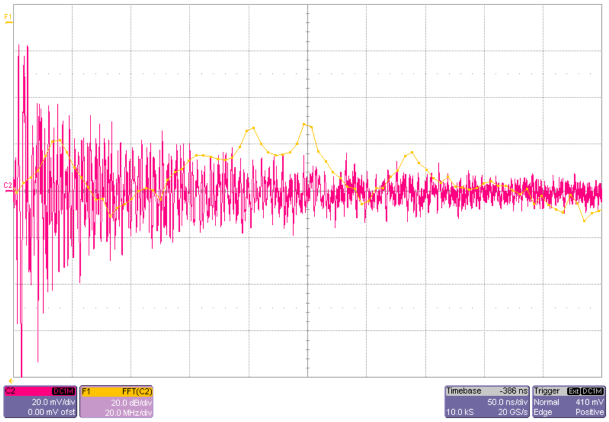

Figure 6: Red trace: superimposed signals of ringing and MO (time domain); Yellow trace: power spectrum showing 1.28 GHz ringing and 1.3 GHz MO components.

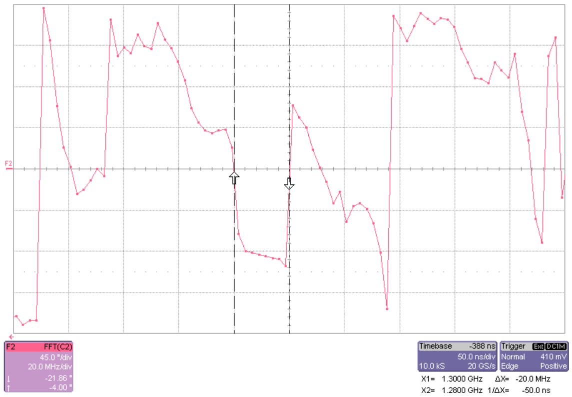

Figure 7: Phases of 1.28 GHz ringing (up arrow) and 1.3 GHz MO (down arrow).

1.313 GHz Local Oscillator (LO) with respect to the Master Oscillator (MO).

The LO, like the MO is part of our “Timing Distribution System”, and as a result the timing jitter of the LO is much less than 1 ps with respect to the MO. This measurement therefore yields the resolution of our application of the Ringing Filter Technique. The distribution of ΔT_{LO} yields an RMS of 1.2 ps. Our data acquisition system therefore has a timing jitter of 1.2 ps.

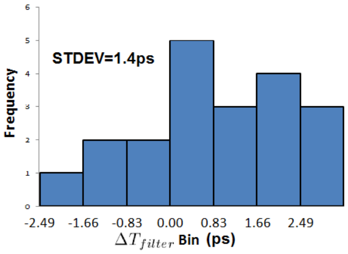

Figure 8: Histogram of ΔT from 20 pulses, STDEV = 1.4ps.

POSSIBLE IMPROVEMENTS

One obvious improvement is to use a better data acquisition system, since the resolution is currently limited by our oscilloscope having a timing jitter of 1.2 ps. But beyond this, the challenge is that we want a short pulse from the photodiode: but the shorter the pulse, the less the excitation energy within the pulse. The difficulty is to accurately measure the phase of a decaying ringing signal with an initial amplitude on the order of mV.

The jitter of a pulse is 1% that of the rise time to a first approximation, and since we are aiming for a pulsed laser timing jitter measurement resolution of less than 200 ps, we need a photodiode with a rise time of less than 20 ps. We have not yet found a commercially available photodiode giving a pulse much larger than 1 V while having a rise time of less than 20 ps.

A potential solution is to put a matching optical cavity in front of the photodiode (Fig. 9). A matching optical cavity is two facing mirrors perfectly aligned, with the distance between the mirrors equal to half the wavelength of the filter downstream. This essentially is a delay line to excite the photodiode (and hence the filter) multiple times to obtain a higher ringing amplitude.

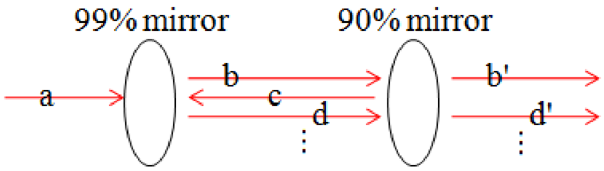

Figure 9: Sketch of an optical cavity.

SUMMARY

We have presented our laser timing jitter measurements. The seed laser timing jitter has been measured to be less than 200 fs, by examining the power spectrum of the signal of a fast photodiode illuminated by it. The pulsed and pumped laser timing jitter has been measured with limited resolution to be less than 1.4 ps, by examining the phase of a cavity impulsively excited by the signal from a fast photodiode illuminated by the laser pulse. This resolution is limited by our oscilloscope, which has a timing jitter of 1.2 ps.

REFERENCES

[1] http://www-a0.fnal.gov.

[2] Jian-Liang Li et al, “Performance of the upgraded laser system for the Fermilab-NIU photoinjector,” Nucl. Instrum. Meth. A564:57-65, (2006).

[3] D. von der Linde, “Characterization of the Noise in Continuously Operating Mode-Locker Lasaers,” Applied Physics B 39, 201-217 (1986).