PERFORMANCE OF THE PICOSECOND TIMING SYSTEM FOR THE *L.I.L.* LASER FACILITY

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ABSTRACT

The CEA has studied a unique picosecond timing system for the Laser Integration Line (L.I.L.), an 8-beam laser currently under construction in France. This laser is the prototype of a future facility dedicated to inertial confinement fusion. It requires very precise beam-to-beam power balancing and timing.

Its timing system had to achieve unprecedented performances : to deliver 800 trigger signals over distances exceeding 300 m with delays individually programmable and near-picosecond range time accuracy.

To achieve this goal, the CEA developed a new design based on very accurate electrical delay generators connected to a master clock through a bi-directional fiber-optic time distribution network. In this article, we describe its principle and present achieved performances.

Keywords *: timing system, picosecond, time transfer*

1. INTRODUCTION

The L.I.L. (*Laser Integration Line*) is a laser facility currently under construction in France. It is the prototype of the future *Laser MégaJoule* (or L.M.J.), a huge laser facility dedicated to inertial confinement fusion (I.C.F.) which will be operating in 2010. It requires a unique timing system with unprecedented performances.

In this article, we describe the principle of this timing system that must achieve near-picosecond range accuracy. We explain the principle of the bi-directional link which makes possible to determine the exact transit time of a long fiber optic, with compensations for the effect of temperature drifts. Finally, we present the general performance achieved by this system.

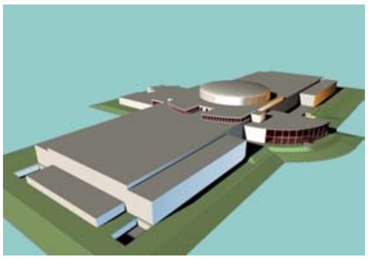

Figure 1 : The LMJ building (30,000 m² ground surface)

2. THE LASER MEGAJOULE PROJECT

The *Laser MégaJoule* will focus 1.8 MJ of U.V. light on a small ball, filled with deuterium and tritium hydrogen isotopes, that will be compressed and heated up to the ignition point. The optical power will be provided by 240 laser beams that must be precisely focused, power-balanced and synchronized. Each laser pulse will have a particular temporal response to generate specific effects such as mechanical compression, plasma heating, and ignition. To control the proper operation of the facility, several kinds of measurement and control systems have to be developed. The timing system is a critical one.

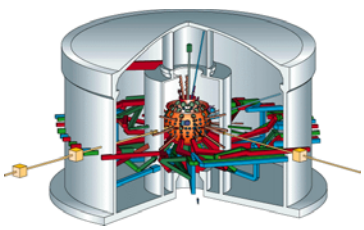

Figure 2 : The 10 m target chamber (at center)

A first milestone in the project was to build a prototype, known as the *Laser Integration Line*. It will feature 8 laser beams, identical to those of the L.M.J. . It is starting to operate in 2002.

Figure 3 : The LIL building

3. REQUIREMENTS OF THE L.I.L. TIMING SYSTEM

The L.M.J. needs a timing system capable of delivering 8,000 trigger signals in single shot mode over an area exceeding 30,000 m², with a dynamic range of up to 2 s, an accuracy ranging from 1 µs down to 5 ps and a jitter ranging from 100 ns down to 5 ps (rms).

The L.I.L. is a smaller facility, but it is still challenging to achieve. The requirements for its timing system were almost the same, beside the lower number of channels (800).

Fortunately an analysis shows that the needs for highest accuracy and lowest jitter triggers corresponds to events which are close to the time of the light impact on the target ($T0_{target}$), while devices needing soon or late trigger are less sensitive. Therefore, to reduce the cost of delay generators, the 800 channels of the timing system were divided in two classes, each of them having a different accuracy and delay range.

Class	Dynamic range	Resolution	Rms jitter	Accuracy
Precise	+/- 50 µs	< 15 ps	< 15 ps	45 ps
Standard (elec. / opt.)	+/- 1 s	< 1 ns	< 100 ps	1 ns + 5 E-7 x delay

Figure 4 : class specifications

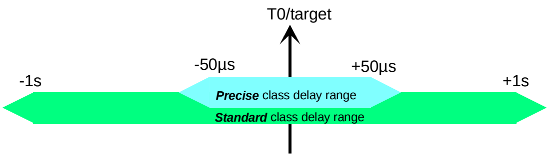

Figure 5 : class delay ranges

Moreover, the analysis of the system showed that :

- each of the trigger output must have an individually programmable delay,
- all delays must be referenced to a common time reference (T_0),
- all trigger outputs must be capable of single shot or recurrent triggering (at 1 Hz, 10 Hz and 100 Hz), all frequencies being synchronous, i.e. a single shot must happen at the same time as a 1 Hz, a 10 Hz and a 100 Hz event (see the chronogram of figure 6),
- the timing system must be distributed throughout the facility (implying cable lengths of 300 m or more).

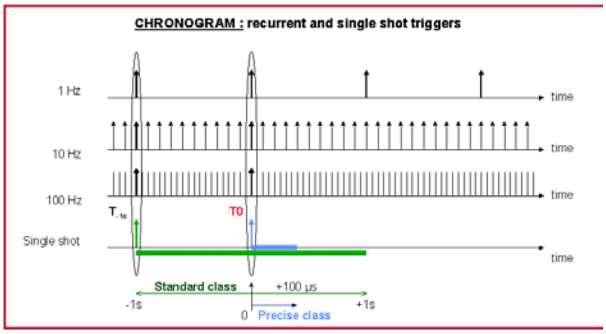

Figure 6 : chronogram of trigger events

4. THE DESIGN OF A DISTRIBUTED TIMING SYSTEM

To face that specific requirements, we needed :

- a highly stable reference clock
- a time distribution network
- many high quality low cost delay generators
- a self-calibration functionality

We conceived a system based on very accurate delay generators connected to a master clock through a bi-directional fiber optic time distribution network.

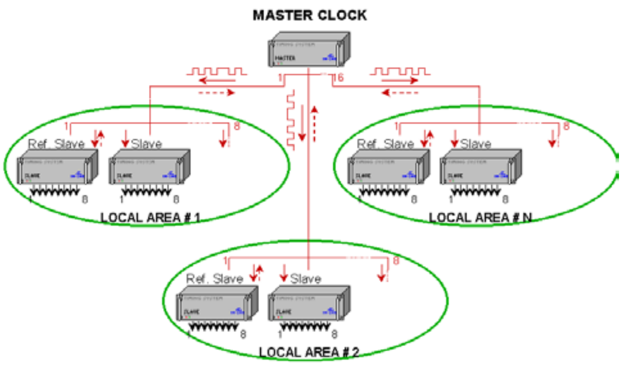

Figure 7: the L.I.L. timing system architecture

4.1 The Master Clock

The master clock is the unique time reference for the facility. It runs a very stable OCXO which is calibrated with an exactitude better than 10^{-8} by comparison to a GPS clock (it can also be permanently locked to the GPS to avoid long term drift). It generates an optical numerical message whose modulation frequency is the image of its internal oscillator, while the data stream is used to send trigger information to delay generators.

4.2 The Optical Distribution Network

A distribution network was designed to distribute the reference clock and trigger information through the entire L.I.L. building. We chose to use a fiber optic network. A careful technical study and economic considerations led us to select a SDH-SONET type link. With a proper choice of components, this permits the use of 155.52 MHz standard components from telecommunications.

4.3 Slave Delay Generators

Slave units are connected to the optical network. They locally recover the 155.52 MHz reference clock and trigger information from the data stream. Each slave device also includes several independent delay generators that drive electrical or optical trigger outputs.

They are based on real time counters that count each period of the 155.52 MHz reference clock, linked to analog time interpolators to generate arbitrary delays with a sub-picosecond resolution. A very careful study was conducted to avoid any problem such as cross-talk, non linearity, noise effects, etc.

4.4 Bi-Directional Links

Fiber optics are easy to use and well fitted to our need, however their propagation delay time varies with temperature changes (from 40 ps/°C/km to 170 ps/°C/km for the fiber samples which we characterized). These variations were not acceptable for our timing system. Therefore, we designed a bi-directional link using two slightly different wavelengths that are separated with WDMs. The two wavelengths are close enough to avoid the effect of chromatic dispersion over several hundreds of meters. One wavelength is used by the master to broadcast time messages to slaves. An emitter which uses the other wavelength was added to some slave units, while an optical converter and a time interval meter were added to the master unit, so that it is possible to monitor propagation delay drifts in the fiber optics by asking the slave to send information back to the master. The same functionality, coupled with a specific installation procedure also gives us the exact absolute transit time of each fiber. In order to reduce the cost of the system, only long fibers are monitored with a bi-directional link. Inside a local area of about 10 m, time offsets between slave systems can be considered as constants, and do not require to be monitored. So only one slave system per local area needs to drive a bi-directional link. We named it the reference slave unit. Figure 7 summarizes the architecture of the system.

The design of this bi-directional link was one of the most critical point of the study.

4.5 Overview

Figure 8 : parts of the timing system

5. Calibration of bi-directional links

Bi-directional links in our system have two purposes :

- to calibrate the absolute transit time of a link within an accuracy of 5 ps, while you can access only one end of the link at a time,
- to monitor variations of transit time of the optical links with temperature changes.

The first functionality is required for the deployment of the system inside the facility. The backbone optical links have a length of 300 m or more. To reach an accuracy of 5 ps, their length must be known with a 1 mm accuracy. But it is not possible to make a measurement with such an accuracy before the fiber is in place inside the building. After, it is not possible any more because you do not have access to both ends of the fiber at the same time and optical reflectometers do not have 1 mm accuracy .

So we designed our master clock and slaves with extra reference outputs that enables the deployment method which we describe here.

5.1 Deployment method - step 1

The idea is to use a short fiber (of a few meters) which is connected to an optical output of the master clock. It must be noticed that we do not need to know the transit time of that fiber.

An optical attenuator is used to adjust the optical power at the same level as it is in the local area which we want to calibrate. That adjustement must be made within 0.1 dB to guaranty the accuracy of the calibration.

Then we connect the reference slave locally to the short fiber.

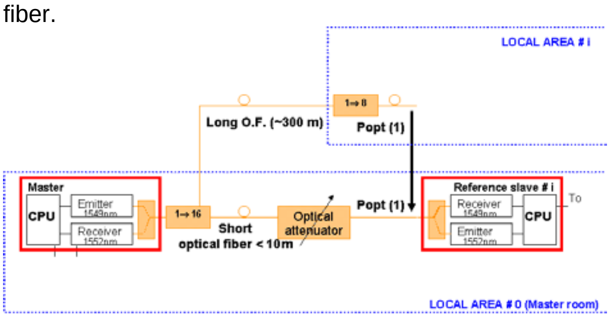

Figure 9 : deployment - step 1

5.2 Deployment method - step 2

The master and reference slave systems are turned into calibration mode.

In that mode, the master sends calibration messages to the slave and issues trigger pulses on its start output.

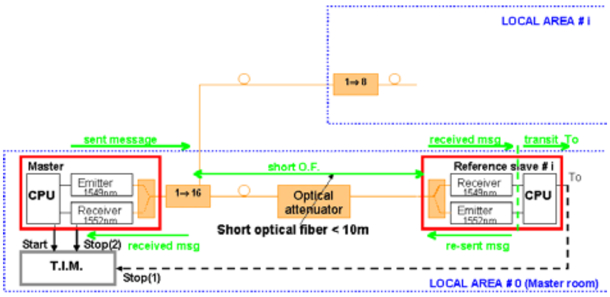

Figure 10 : deployment - step 2

The slave receives them, issues trigger pulses on its To output, and sends the messages back to the master. The master receives them and issues trigger pulses on its stop output.

Two measurements are made with a picosecond time interval meter (T.I.M.) as shown on figure 2 :

K1 (Start/To) = delay (emitter 1 + short O.F. + receiver 2 + delay To)

K2 (Start/Stop local) = delay (emitter 1 + (2 x short O.F.) + receiver 2 + emitter 2 + receiver 1)

The measurement of K1 is possible because the slave is close to the master, so that its To output can be connected to the T.I.M.

5.3 Deployment method - step 3

Then the reference slave is put back in its local area. The master and the slave are set in calibration mode again, and we make a third measurement:

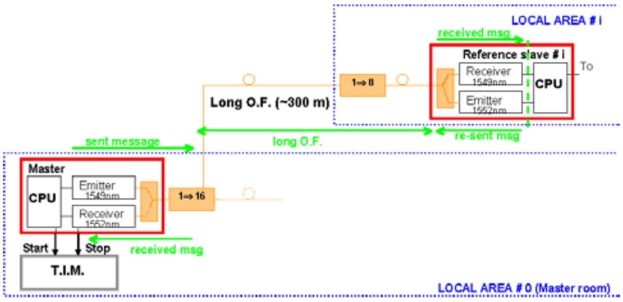

Figure 11 : deployment - step 3

K3 (Start/Stop zone) = delay (emitter 1 + (2 x long O.F.)
+ receiver 2 + emitter 2
+ receiver 1)

It is then possible to calculate the propagation delay between the start output of the master and the To output of the slave:

$$\mathrm{Start/To} = \frac{K3 - K2}{2} + K1$$

That method must be applied for each of the 16 local areas in the L.I.L. building.

5.4 Deployment method - step 4

Within each local area, other slaves are time-aligned with the reference slave by a relative measurement between their To outputs.

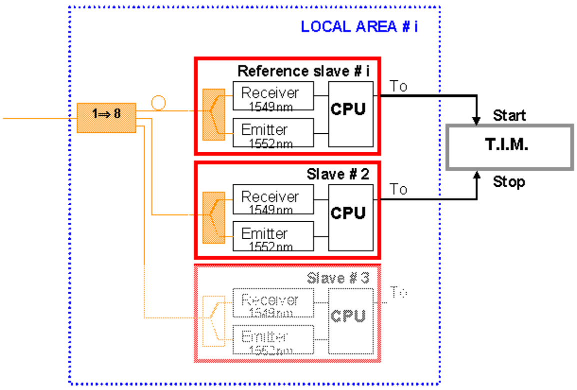

Figure 12 : deployment - step 4

All computed values are entered in a correction table managed by the supervision system of the facility.

6. TEMPERATURE DRIFT COMPENSATIONS

The master clock and slaves have internal temperature corrections. Each delay is corrected as a function of the current temperature and also of temperatures registered during steps 1 to 4 of the calibration process.

Temperature drift of optical fibers is compensated through a self-calibration process of the system. Periodically, each reference slave is turned into calibration mode and the K3 parameter is updated (the same way as shown in figure 11). Depending on temperature changes and accuracy expected in a local area, the periodicity may differ.

7. ACHIEVED PERFORMANCES

The delivery of the 800 channels of the Timing System for the L.I.L. has been achieved. The system is now under deployment. Several zones are already operated and demonstrate the good performances of the system :

- the stability over 48 hours is not measurable (the drift is under the 5 ps accuracy of our T.IM.),
- the jitter between two channels of different slaves (worst case) is under 10 ps (including 3 ps for the T.I.M.),
- the linearity error which we measured between 2 channels over a delay range of 0.1 ms did not exceed -14 ps or +8 ps,
- the typical accuracy is : $\pm$ 20 ps $\pm$ 1.5 10^{-7} x T (ps),
- the sensitivity to optical level on the link implies a careful measurement during deployment (this point must be enhanced on the L.M.J. timing system).

All measurements show that performances conform to or exceeds the initial requirements and almost meet those of the L.M.J..

8. TOWARD THE L.M.J. TIMING SYSTEM

Our laboratory is working in order to achieve accuracy close to 1 ps in the electrical time domain and under 10 ps for optical to electrical measurements over a 10 µs range. We are developing new methods, combining different kinds of existing instruments, looking for new ones, ... or developing some new products such as picosecond streak cameras for our needs.

These efforts, started one year ago, must give us the capability to qualify the performances of the L.M.J. timing system within 2 years.

9. CONCLUSION

The L.I.L. Timing System is a unique system with very high accuracy (< 45 ps) and very low jitter (< 10 ps). It meets or exceeds its original specifications.

The scalability of the system makes it adaptable to other applications requiring precise timing. With much or less modifications, it can be used as a basis for :

- other experimental facilities requiring picosecond or nanosecond timing,
- to propagate a reference clock between several buildings,
- to synchronize real time parallel computers,
- …

The L.M.J. timing system will also be based on the same principle. It will benefit of the feedback from the L.I.L. and from our picosecond measurement effort.