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LASER MEGAJOULE TIMING SYSTEM

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Abstract

The "Laser MégaJoule" (LMJ) timing system, under development since the year 2000 and tested on the "Ligne d'Intégration Laser" (LIL), laser facility (prototype of LMJ), is now entering in his final commissioning and installation. To synchronize the laser beams on the target better than 40 ps rms, the timing system needs to produce electrical pulses with jitter lower than 5 ps rms and drift limited to 20 ps peak to peak. These requirements have been reached with the last evolution of delay generator in our distributed optical architecture.

INTRODUCTION

The LMJ facility is a high-power laser designed to deliver about 1.4 MJ of laser energy to targets for high energy density physics experiments, including fusion experiments [1]. This energy is produced by 176 laser beams gathered in quadruplets of 4 beams. Each quadruplet is equipped with an Arbitrary Waveform Generator (AWG) that generates the desired temporal pulse shape (lasting typically 3 ns). Synchronization of LMJ's 176 laser beams is crucial to compress symmetrically the millimeter-size target in order to ignite the deuterium and tritium filled capsule. The most demanding experiences need to synchronize the quadruplets to better than 40 ps rms despite the fact the quadruplet laser sources are separated within the building by several hundred meters. In addition to laser beams synchronization, the LMJ timing system is in charge to deliver, with the same or lower accuracy, two kinds of signals: fiducials for both temporally mark signals and plasma diagnostics, and triggers signals for manifold devices (sources, amplifiers, Pockels cells, diagnostics...).

The synchronization is therefore one of the most important components for shot experiment, from the laser sources to the target inside the chamber, as shown in Fig. 1.

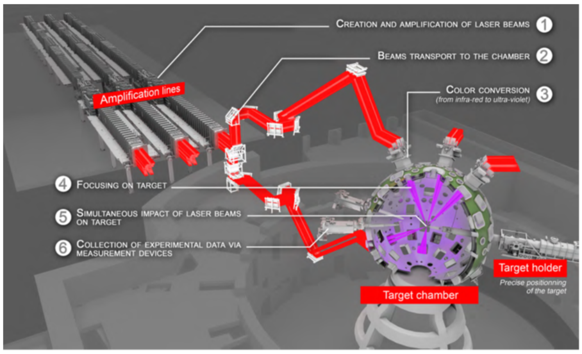

Figure 1: From laser amplification to experiment in the chamber.

The error budget calculus to reach the 40 ps rms specification has showed that the requirements for the timing systems were the following [2]:

- < 5 ps rms jitter or 8 ps rms between 2 outputs
- < 10 ps p-p drift / 24 hours
- < 20 ps p-p drift / 1 month

LMJ TIMING SYSTEM

As seen previously, the LMJ requires a lot of timing channels with different accuracies. From 2002 to 2013, three levels of timing system were defined [2] [3] [4] until new data were analyzed from:

- LIL prototype,
- First laser beams on LMJ facility,
- Measurements by Greenfield Technology (GFTy).

Finally, the second and third level timing systems were merged in only one High Precision Timing system (HPT) in complement to the Standard Precision Timing system (SPT), Fig. 2.

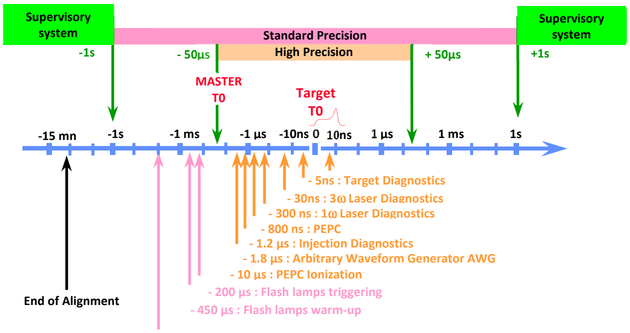

Figure 2: New LMJ synchronization time line.

Table 1 below summarizes the actual requirements of the two levels of precision:

Table 1: LMJ Timing System Requirements

Precision	Jitter rms	Temporal Drift peak to peak			Accuracy	Range
		24 h	7 days	1 month		
Standard (SPT)	<150ps	<200ps	<500ps	<1ns	<±1ns	1s
High (HPT)	<5ps	<10 ps	<20ps	<20ps	<±10ps	100µs

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TIMING SYSTEM ARCHITECTURE

The architecture of the LMJ timing system is based on:

- A LMJ master clock, the time reference, which delivers an optical clock coupled with triggering data. This oscillator is stabilized with GPS connection or rubidium oscillator to avoid long term drift.
- An optical distribution network in charge to send the optical data clock signal through the whole LMJ facility.
- Two slaves classes (delay generators), depends on time precision needs.

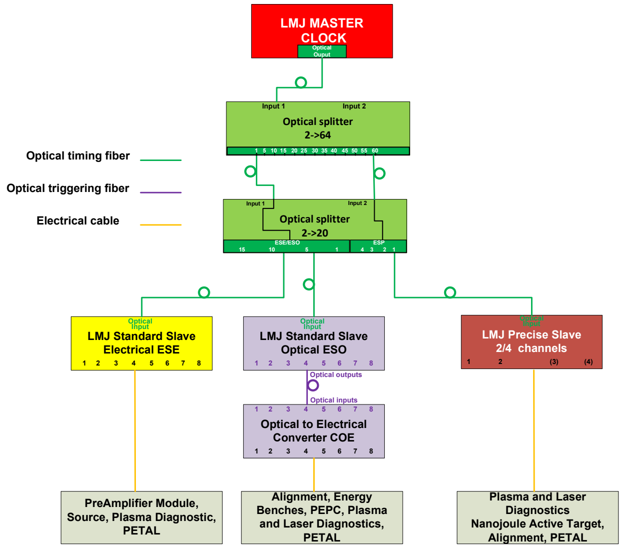

Figure 3: LMJ timing system architecture.

The principle of the timing system is to send time data information within a reference clock to the slaves connected through the optical timing network (in green, Fig. 3). The reference clock, recovered by each slave, is based on the well-known 155.52 MHz SDH-SONET standard communication protocol. So, each connected slave receives the stream data with triggering information and generates programmed delays for each output with the precision of its class.

TIMING SYSTEM: ONE LASER BUNDLE

The LMJ facility is divided in 4 laser bays (128 meters long) with 5 to 7 bundles of 8 laser beams. Each laser bundle needs 14 slaves (10 standard slaves and 4 precise slaves), 14 optical to electrical converters and more than 50 optical fibers to synchronize it.

Each optical fiber and equipment (slave, optical splitter, optical to electrical converter) must be time calibrated (channel by channel) to start the laser beam synchronization with a “clean slate”.

Figure 4: Main room of the LMJ timing system.

It takes 4 weeks to install all the “synchronization components” and one more for time measurements (the optical fibers must have been installed previously).

Nevertheless, any change in the configuration, like a broken optical cable, leads to make a new measurement to update the LMJ time configuration.

To fulfill the 22 laser bundles, the synchronization requires more than 300 slaves and 1100 optical fibers (Fig. 4).

TIMING SYSTEM FOR TARGET CHAMBER DIAGNOSTICS

The 4 laser bays of the LMJ facility are grouped in pairs on two opposite sides of the target bay (cylinder 60 m diameter and 38 m height). Inside, the aluminum sphere (10 m diameter – 10 cm thick) is equipped with several ports to introduce laser beams and diagnostics. These diagnostics need to be synchronized to measure ultrafast events on shot experiment.

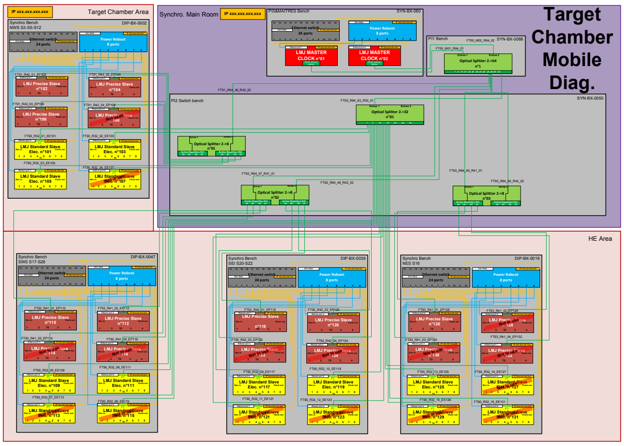

Figure 5: Target chamber diagnostics, timing system description.

Diagnostics synchronization of the target chamber (Fig. 5) requires more than 100 slaves and 100 optical fibers.

TIMING SYSTEM COMPONENTS

Greenfield Technology (GFTy), which designed the first timing system for the LIL facility, has been hired by CEA to develop new products to meet the LMJ requirements. Besides, GFTy also designed, on the same principle, the timing system for the AIRIX/EPURE facility (Radiographic X-ray machine) at CEA/VALDUC near Dijon, France.

The timing system architecture, as previously described (Fig. 3), leaded to design a new master clock oscillator, four specific optical splitters, three kinds of optical to electrical converter and two classes of delay generators (slaves).

LMJ Master Clock

The LMJ master clock (Fig. 6), connected to a GPS/rubidium oscillator, converts stable 10 MHz signal to a standard optical frequency (155.52 MHz) within a single-mode optical fiber.

Figure 6: LMJ Master Clock.

The 12 dBm (≈16 mW) optical power output was defined to provide, after two passively split, the power needed for the optical input of each slave.

The LMJ master clock is the heart of the system; it provides different timing information like:

- 3 frequencies: 1 Hz, 10 Hz and 1000 Hz.
- Single-shot with 3-time references: SS0 (-2 s to -30 s), SS1 (-1 s) and SS2 (0 s).

Passive Optical Splitter

The two slaves classes used on the LMJ facility need different optical power inputs to reach their precision: about -25 dBm for standard slaves (optical and electrical) and -18 dBm for precise slaves. This is the main reason why four different splitters were developed (Fig. 3 and 5):

The LMJ master clock is the heart of the system; it provides different timing information like:

- Main splitter: 1 x 64 (first splitter).
- Standard splitter: 1 x 32 (for standard slaves).
- Precise splitter: 2 x 8 (two 1 x 4 for precise slave).
- Asymmetrical splitter: 2 x 20 (1 x 16 + 1 x 4 for both slaves).

Optical to Electrical Converter

Standard Optical Slaves (ESO) have been made for triggering diagnostics with optical input and also diagnostics located in a specific area (high energy room for example) where electrical slaves cannot be installed. For this reason, three different optical to electrical converters (COE) have been designed:

- Single channel: COE 1 x 1.
- Multiple channels: COE 8 x 8.
- Single to 4 split channels: COE 1 x 4.

Characteristics of optical and electrical signals are shown in figure 9.

Delay generators (slaves)

They are the main components of the timing system. They have to generate delays compatible with the LMJ timing specifications (Table 1) all over the facility. To reach the LMJ's 2 classes of precision (standard SPT and high HPT), 2 different delay generators were designed by GFTy:

- Standard slave (GFT1018, Fig. 7):
    - electrical (ESE) with 8 electrical outputs (BNC connector)
    - optical (ESO) with 8 optical 1310 nm outputs (SC/PC).

This last version can be used with an optical to electrical converter.

Figure 7: Standard and precise slave

- Precise slave (electrical, GFT1012/1014, Fig. 8):
    - 2 BNC outputs (EP2V)
    - 4 BNC outputs (EP4V)

Figure 8: Precise slave.

All slaves have an optical input connection (SC/APC) to receive the optical master frequency, an external clock output (BNC, 9.72 MHz), a reference signal output (BNC) and a trigger input (BNC).

Furthermore, fiducial signals and triggers ones have been merging in one reference signal.

Figure 9 shows the main electrical and optical slaves outputs specifications:

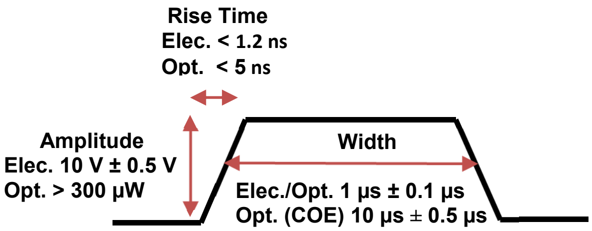

Figure 9: Electrical and optical slaves outputs specifications.

Slave resolution is 1 ps and the programmed delay must be in a range of 1 s for standard slaves and 100 µs for precise slaves.

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In addition, the LMJ master clock and slaves have internal temperature correction and the optical fiber used has free space between cladding and coating.

The typical variation of temperature inside a bench of the LMJ facility is under 0.3°C rms. The slaves must therefore be installed on the bottom of bench to ensure that the operating temperature is between 20°C and 25°C (Fig. 10).

If a temperature or a delay issue is identified, a warning is sent to the operator.

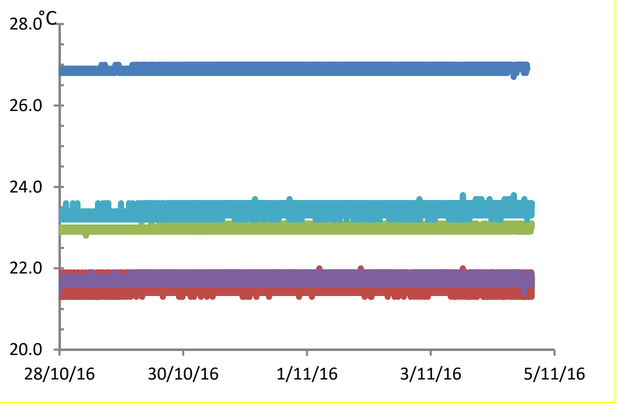

Figure 10: Temperatures inside a LMJ bench at different levels (from bottom to the top).

SLAVES PERFORMANCES

Table 2 below shows the main slaves specifications required for the LMJ timing system:

Table 2: Slaves Specifications

Slaves	**Jitter rms 2 channels / 2 Slaves**	**Temporal Drift peak to peak**			**Accuracy**	**Range**
		24 h	**7 days**	**1month**		
Electrical Standard	<100ps	<200ps	<500ps	<1ns	<±1ns	1s
Optical Standard	<150ps	<200ps	<500ps	<1ns	<±1ns	1s
Precise	<5ps	<6ps	<10ps	<20ps	<±10ps	100µs

All measurements have been performed on precise slaves in multiple “single shot mode” by the CEA (Fig. 11) as well as in recurrent mode (1 kHz) by GFTy.

The master clock is connected to one or two slaves and the digitizer records the reference output (split on 2 channels). The 2 others channels record either the reference clock and an output of the same slave (Fig. 12) or an output of each of two different slaves (Fig. 13).

Figure 11: CEA measurements in controlled environment.

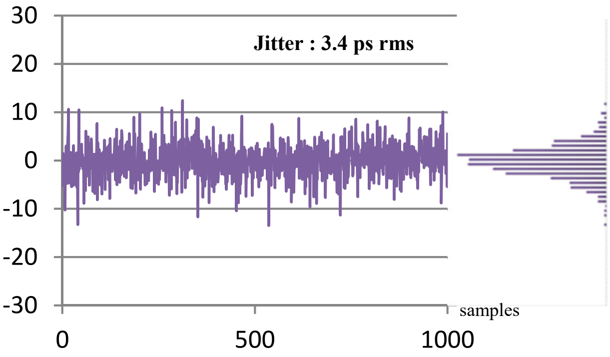

Figure 12: Jitter between 2 outputs/same slave.

The 3.4 ps rms jitter between two electrical outputs of the same precise slave (n°17) has been verified on the second precise slave (n°5): 3.7 ps rms.

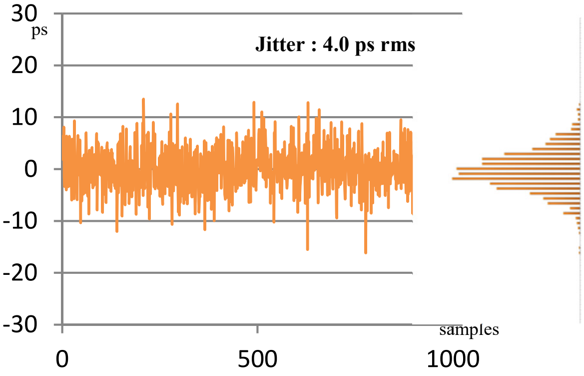

Figure 13: Jitter between slave n°5 output 1 and slave n°17 output 1.

These jitter measurements (4.0 ps rms) confirmed the GFTy’ ones (3.8 ps rms) in recurrent mode (with also 2 different precise slaves).

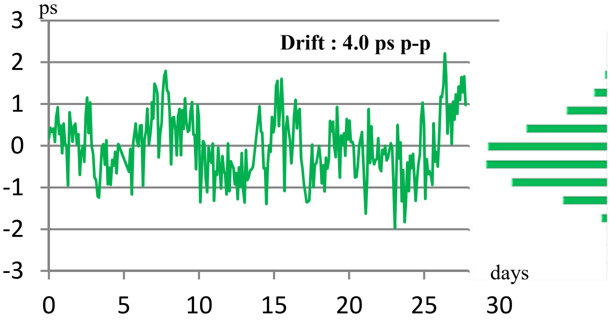

Figure 14: Temporal drift over 1 month.

To measure the temporal drift, a sequence of 255 single shots is performed every 2 hours during 1 month. The average value is calculated for each sequence to reduce jitter impact. Figure 14 shows the evolution of this mean value versus time which defines time stability. The temporal drift measurement over 1 month is close to 4 ps p-p which is better than the LMJ drift requirement (Table 1).

The accuracy of our synchronization system has been verified to be ± 10 ps and the sensitivity to the temperature is below 1 ps/°C (GFTy measurements).

The next step is to check on site the performance of our synchronization system. We therefore plan to install, before the end of the year, a measurement system close to the target chamber.

Even if our Timing System meets our requirements, it can still be improved. Some axes of ameliorations are presented by GFTy [5].

FEEDBACK FROM DEPLOYMENT AND OPERATION

Standard slaves are in service for 3 years and precise slaves for a few months. Two minor defects have been observed without any impact on LMJ schedule. Hardware and software updates have been implemented to solve them.

Most of the problems encountered on the installation come from wiring problems (fiber optic network and computer network) as well as the setting up of the computerized maintenance management system (CMMS). Figure 15 shows for example the localization of a broken optical fiber via the injection of a red laser source.

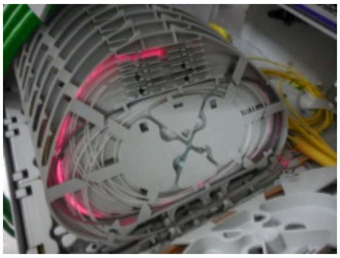

Figure 15: Broken optical fiber detected with red laser.

CONCLUSION

The LMJ timing system is now operational on 8 laser bundles plus PETAL (high energy PETawatt Aquitaine Laser) and the 14 last laser bundles will be installed before 2022. More than 1000 fiducial/triggers signals are generated, and more than 2500 will be when all slaves will be installed.

Jitter has been measured under 4 ps rms and temporal drift over 1 month has been measured close to 4 ps p-p. These performances meet the precise timing system requirements and will be the cornerstone to synchronize the LMJ to better than 40 ps rms.

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