EVOLUTION OF THE LASER MEGAJOULE TIMING SYSTEM

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Abstract

The Laser MégaJoule (LMJ) timing system has been fully provisioned at the end of 2022. With 15 bundles, 120 beam laser, at the end of 2023, the operational capabilities of the LMJ facility are increasing gradually until it's the full completion by 2025.

The performance of the synchronization equipment on the LMJ is picosecond class. Since 2013/2014, CEA ha continued our studies to improve performance. In 2023, CEA has introduced new features such as a 500 ps rise time at 1 V, variable width and dynamic fine tune delay calibration to improve precision.

Meanwhile, due to electronic obsolescence, a new modified prototype precise delay generator, with "new and old channels", has been tested and compared.

INTRODUCTION

The LMJ facility is a high-power laser designed to deliver about 1.4 MJ of laser energy to target 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 that 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 marked 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.

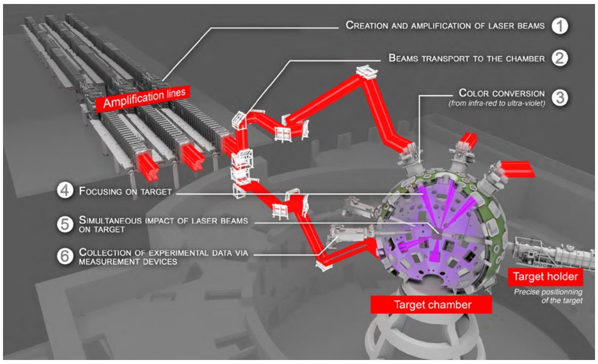

Figure 1: From laser amplification to experiment in the chamber.

The error budget calculus to reach the 40 ps rms specification has showed that the requirements for the timing systems [2] were, for the most precise delay generator, less than 5 ps rms jitter between 2 outputs and 10 ps p-p drift / 1 month.

LMJ TIMING SYSTEM

As seen previously, the LMJ requires a lot of timing channels with different accuracies. After choosing to only have 2 levels of timing system precision [3], the CEA timing system team adapt the time line with 3 reference timing triggers, SS0, SS1 and SS2, and 3 reference frequencies, Fig. 2.

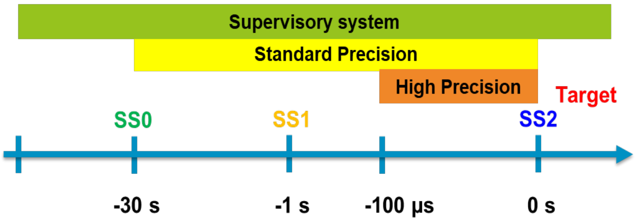

Figure 2: LMJ synchronization time line.

Table 1 below summarizes the LMJ synchronization requirements and measurements [4] of the two levels of precision by equipment:

Table 1: LMJ Timing System Requirements

Classes of performance Precision Delay generator	Jitter rms	Temporal Drift peak to peak			Precision	Range
		24 hours	7 days	1 month		
Standard	<100 ps	<200 ps	<500 ps	<1 ns	<±1 ns	1 s
High Specification Measurement	<5 ps 4 ps	<6 ps 4 ps	<10 ps 4 ps	<20 ps 4 ps	<±10 ps	100 µs

TIMING SYSTEM ARCHITECTURE

The architecture of the LMJ timing system is still unchanged:

- A LMJ master clock, the time reference, delivers an optical clock coupled with triggering data. This oscillator is stabilized with GPS connection, or rubidium oscillator, to avoid long term drift.
- A passive optical distribution network sends the optical data clock signal through the whole LMJ facility.
- Two delay generators classes, one for each precision classes, receive the optical information and generate programming delays.

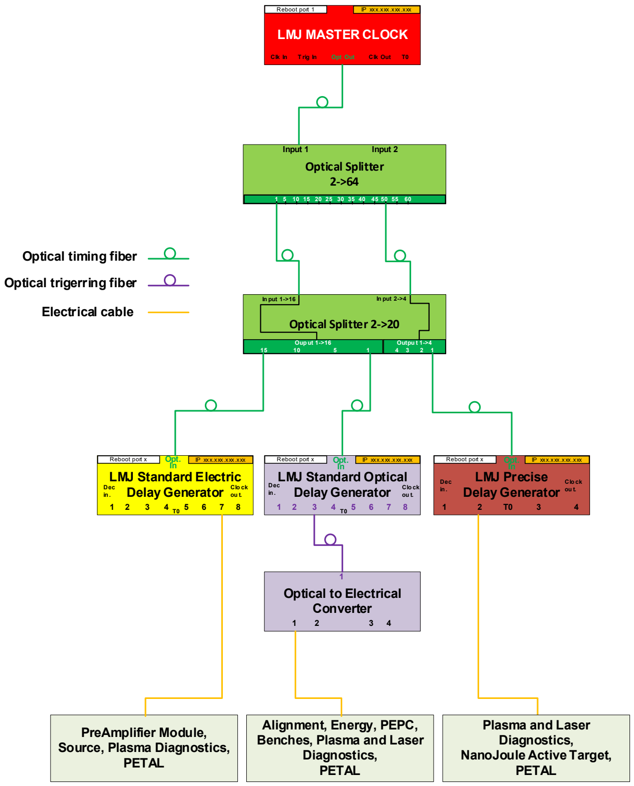

Figure 3: LMJ timing system architecture.

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

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

This 4 laser bays 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.

To fulfill the 22 laser bundles and the diagnostics, the synchronization requires more than 340 delay generators and 1400 optical fibers [3].

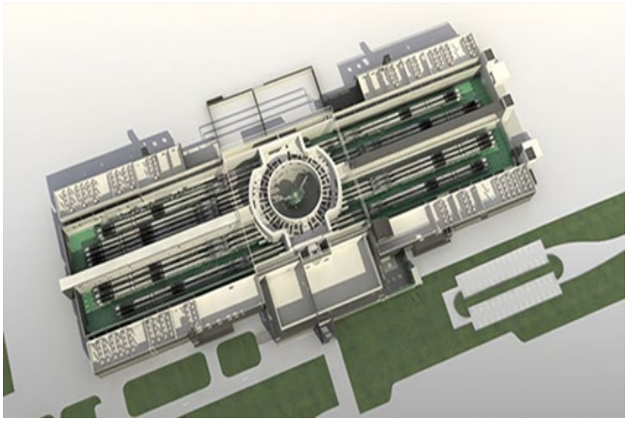

Figure 4: upper view of the LMJ Facility.

LMJ TIMING SYSTEM: EVOLUTION TO MANAGE OBSOLESCENCE

Since 2017 and the installation of the first delay generator, the synchronization equipment is still the same as the original [3]. Even if some hardware correction and software evolution have been realized, and are always in progress, there was no conception or electronic study.

In 2019, with the new chipset GENEPIC developed by CEA-Leti and Greenfield Technology [5], and the post-COVID electronic issue, some components were no longer available. So, to manage obsolescence, the choice was made to use the new GENEPIC chipset inside the precise delay generator (GFT1012) to replace the actual fine delay module. The challenge was to keep all the timing specifications unchanged in particular the jitter and the drift.

GENEPIC chipset has 2 news functionalities for the timing system: dynamic fine tune delay calibration to improve precision and the possibility to generate a very precise width (mix 2 channels).

To maintain ultra-high precision of the delay generator, he same precautions had to be taken to avoid noise and thermal instability. In consequence, the electronic and the mechanic design outside and inside (box in the box concept) are similar from the older one and the specific GFTy CDR function is retained [6].

An original 4 channels delay generator was modified to include 2 new channels (1 and 2) to integrate this new GENEPIC module (Fig. 5).

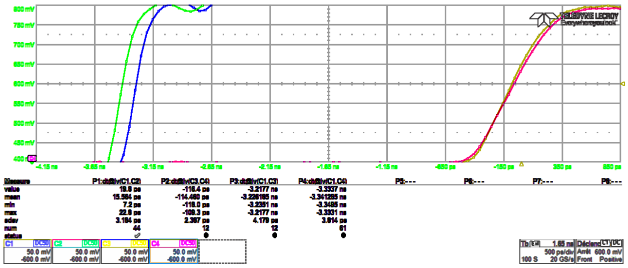

Figure 5: Screenshot of new GENEPIC signals (green and blue) and old signals (red and brown).

This prototype was then tested to determine its specificities in terms of jitter, drift and temperature sensitivity. Conditions of this test are shown in the measurement diagram (Fig. 6) and photo (Fig. 7) show.

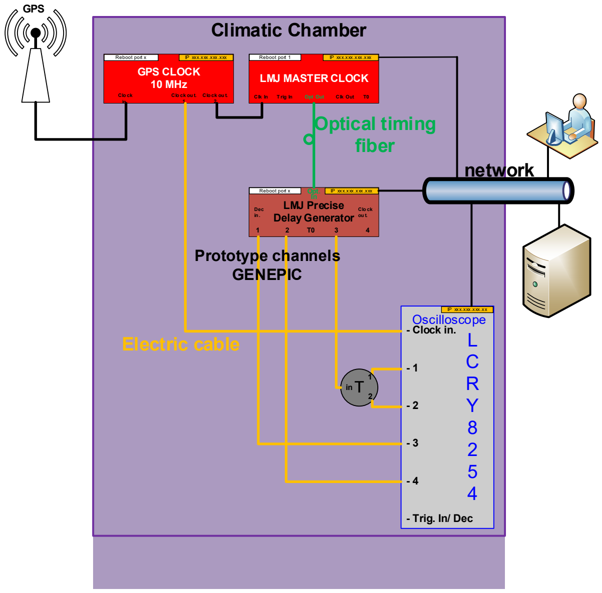

Figure 6: Measurement diagram.

Figure 7: Measurement conditions.

For the jitter measurement, 1024 single acquisitions are realized for several delays from 0 ns to 9 ns. The difference between the 2 new outputs is calculated with its jitter associated.

In first, this jitter is very close to the previous value the CEA timing system team had measured [3] in 2019 for the same type of precise delay generator: 4 ps (Fig. 8).

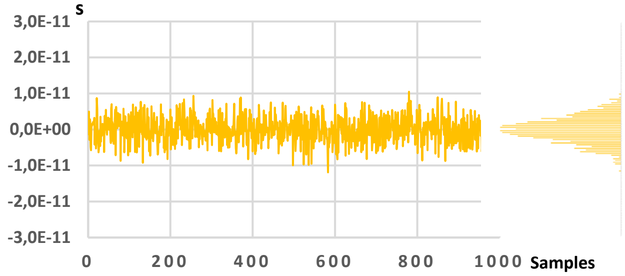

Figure 8: Jitter of the prototype precise delay generator.

To verify the accuracy of the jitter measurement, the time dependent jitter of the new GENEPIC module was check at 0.8 ps (Fig. 9).

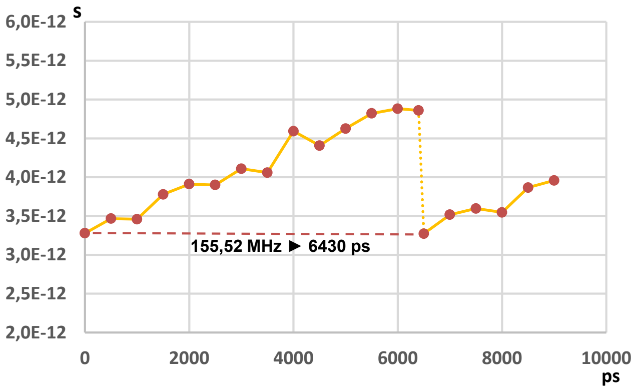

Figure 9: Jitter over fine delay of the new precise delay generator.

In second, the thermal influence is one of the main characteristics. So the measurement jitter over temperature has been characterized from 15°C to 30°C (Fig. 10).

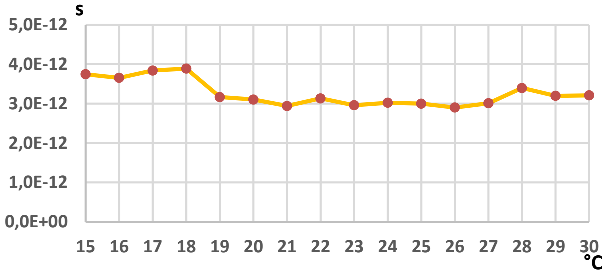

Figure 10: Jitter over temperature of the new precise delay generator.

This measurement confirms that there is no significate variation of the jitter (3 ps ± 0.2 ps) when the temperature is stabilized from 20°C to 25°C.

To finish, the drift over time measurement has to be check with this new configuration. The process is unchanged a sequence of 256 single shots is performed every hour during 1 month. The average value is calculated for each sequence to reduce jitter impact. Figure 11 shows the evolution of this mean value versus time which defines time stability.

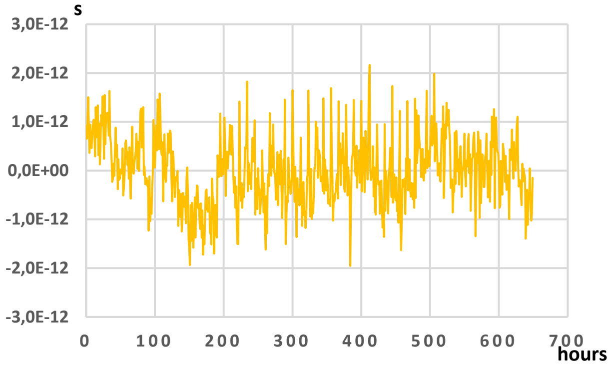

Figure 11: Temporal Drift over 1 month.

The temporal drift measurement over 1 month is close to 4 ps p-p which is similar to the older value with the current precise delay generator and still better than the LMJ drift requirement (Table 1). The temporal drift includes also the drift of the oscilloscope.

CURRENT STATUS

At the end of 2023, the LMJ timing system is operational on 18 laser bundles plus PETAL (high energy PETawatt Aquitaine Laser) and the last 4 laser bundles will be installed before the end of 2025.

More than 500 of the 700 pieces of equipment are installed and used every day, 24 hours a day, 7 days a week, 365 days a year.

The number of breakdowns per year, in relation to the number of units, is around 7.10^{-3} since the introduction of a procedure to check that the equipment is correctly operating every year for the past 4 years. Thanks to this relatively low rate, we have close to 100% availability.

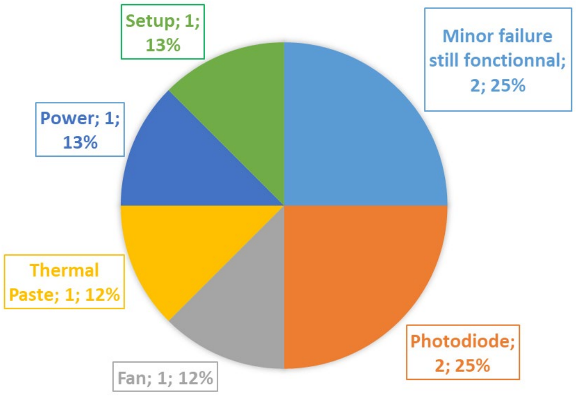

Figure 12: Type of repairs in 2022.

The identification of failures has made it possible to determine the nature of the components involved (Fig. 12). Most failures can be repaired either immediately (fan, power supply, setup) or in less than a week (thermal paste, photodiode).

The first synchronization diagnostics to check the fiducials at 1ω and 3ω are currently being deployed on the LMJ facility for testing on several laser bundles.

The principle is based on the use of reference signals from each precise delay generator, which are then multiplexed by hall before being grouped together on a single oscilloscope (70 fiducials signals on 6 channels). Once the experimental phase has been completed, to define the expected level of precision, this diagnostic system will be deployed on all laser chains.

THE FUTURE OF SYNCHRONIZATON

Managing the obsolescence is not our only objective. At the same time, the CEA timing system team plan to add new time references, new higher frequencies and a fiber optic temporal measurement system for each delay generator.

The ultimate goal is to have a self-calibrating automatic synchronization recognition system.

The CEA timing system team have already started working on a new delay generator (standard class) with new features: Gaussian outputs (elec. and opt.), variable level, optical outputs (for several wavelengths).

Finally, this new equipment must be able to integrate into a new architecture where the old and new synchronization systems could be mixed without modifying the existing optical network.

All these new specifications are also aimed at improving performance and using the same type of synchronization for all the CEA's major facilities (LMJ, EPURE…).

CONCLUSION

The evolution of LMJ synchronization is designed to maintain the same level of performance for both laser bundles and diagnostics. The replacement of the critical component used to fine-tune the delay within each precise delay generator has been achieved while retaining its main characteristics: 4 ps of jitter and 4 ps of drift. In addition, this replacement was carried out by a component developed specifically by Greenfield Technology.

Further developments are underway to improve the performance and functionality of future delay generators, whatever their accuracy class. One of these is aimed to bring synchronization as close as possible to the recording systems associated with diagnostics.

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