Ultrashort Pulse gating:

The New Reliable Cornerstone in Particle Accelerators

Introduction

For decades, particle accelerators structures relied on electromagnetic interactions. Obviously, laser waves have been intensively investigated as key elements, due to their unique capabilities in terms of directivity, potential intense electric fields and wavelength tuning. Unfortunately, early attempts have evidenced some drawbacks, such as very low overall stability, poor long-term reliability and delicate maintenance, that have precluded an efficient development as initially expected.

The recent introduction of lasers into key particle beam processes, from the production of particles by photoelectric effect to the interactions themselves, is currently experiencing rapid revival thanks to the extreme reliability and flexibility of new laser architectures. In the last few years, tremendous laser improvements, including rugged technology virtually maintenance free, have been implemented that reenables many previous designs in particle accelerators. The wide field where lasers can be an unprecedented tool spans from simple interaction involved in the production of photo-electrons, to the more recent strategies where powerful lasers can produce the driving force itself in wake field acceleration or more generally in Particle-Plasma interaction. Generally, short laser pulses provide the required peak energy required in these applications, but non-extreme laser architecture - picosecond pulse train and milijoule (mJ) energy- can still fulfill most of the parameter requirements in this field of particle accelerators.

We will first introduce some applications benefiting from picosecond to nanosecond pulse trains at the mJ level. Some are already implemented (Photo extraction of electrons), other foreseen in a near future in interaction with accelerated electrons (Inverse Compton effect and Ultrafast electrons dynamics). Then we will describe how our proprietary pulse gating technology implemented in the rugged MANNY series from IRISIOME SOLUTIONS, can easily fulfill various experimental requirements and enhance the overall efficiency of many processes in the field of particle acceleration.

Application Field in Particle Accelerators Structures

1. Photo Excitation of Cathodes

The first use concerns the excitation of photocathodes for electrons extraction. As accelerators structures rely on electron bunching at MeV energy, a production of electron bursts using a high repetition rate pulsed laser shining a photocathode is particularly well adapted (Fig 1).

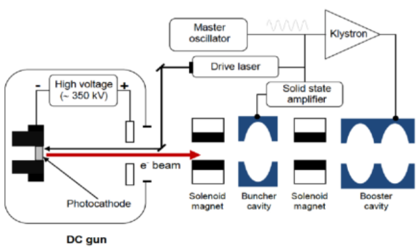

Figure 1: Photoinjection and accelerator structure (Principle)

The performance of this technology relies first in a perfect synchronization (temporal jitter of few ps RMS) in order to generate an electron beam in full synchronism with the accelerator structure. Moreover, homogeneous transverse spatial structure and Top-Hat temporal profile pulses will greatly improve the overall geometric quality of the electron bunches by reducing the impact of space charge on the beam emittance. Finally, many existing installations using semiconductor-based photocathodes require high energies per pulse in the visible and use (or have used) solid-state laser technologies of the Nd:YAG amplifier type with a conversion stage of frequency.

IRISIOME SOLUTIONS products can replace all or part of this equipment, from the master oscillator to the amplifiers and the frequency converter. This rugged industrial equipment proposed by IRISIOME SOLUTIONS, nearly maintenance free, does not required specific technical skills in laser technology as in other available solutions.

Large particle accelerators installations have already upgraded the front stage of the electrons production using the MANNY laser (CEA/DAM Bruyeres le Chatel, France; US DOE Brookhaven National Lab USA). Our technology greatly improves the ease of use, and enables a fine tuning of the whole process while playing with open parameters such as pulse duration, repetition rate and fine wavelength tuning.

In addition, it would be possible to propose sources at wavelengths close to U.V (<0.4 mm) allowing to excite more reliable metallic photocathodes requiring less energetic photons. These near UV wavelengths are easily reached by third or fourth harmonic generation.

2. Interactions with Accelerated Electron Beams

- **X-rays Production by Inverse Compton Effect**

The production of X-rays for non-destructive imaging in the fields of research, healthcare, nuclear security and the preservation of cultural heritage requires reliable sources of electron production. Among the methods used, the one based on inverse Compton scattering involves the interaction between accelerated electron packets and visible, IR or UV photon packets (Fig 2).

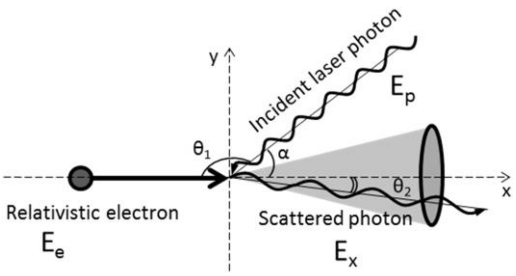

Figure 2: Inverse Compton Effect Principle

If the implementation of our systems in the initial step of photocathode excitation is considered as an innovation, we strongly emphasize that their use in the interaction itself could greatly benefit from the temporal qualities of wide flexibility, synchronism as well as beam shape in accumulative photon systems, for "pile-up" architectures [1, 2] or even in the ThomX project [3].

- **Ultrafast Electrons Diffraction**

This approach allowing the study of matter at very short time scales is based on simultaneous illumination of a material by an electron beam and an ultrashort laser beam (laser Pump- electrons Probe) (Fig 3). The study of the diffraction pattern of electrons after laser excitation enables a precise description of the structure dynamics of the matter with very high precision [4]. Introduced in 2003 by A. ZEWAIL, (Nobel Prize in Chemistry), this approach is currently undergoing very rapid development. Here again, the properties of the IRISIOME SOLUTIONS lasers are particularly well suited to these experiments.

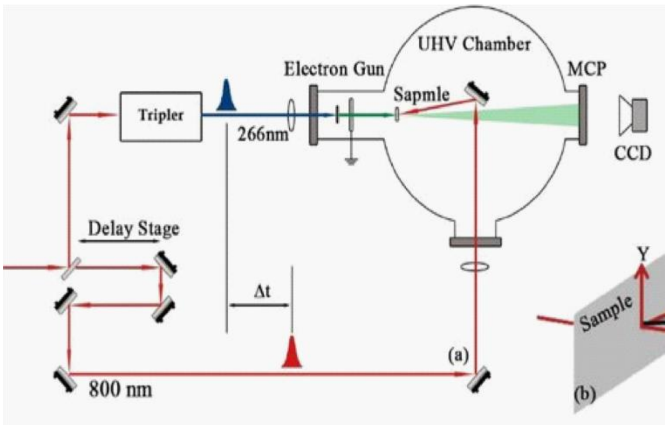

Figure 3 : Principle of Utrafast Electron Diffraction

References

[1] Y. Suzuki and T. Ikehata.Washington, DC, US Patent 6487003, 2002.

[2] A. Chaleil, V. Le Flanchec, A. Binet, J. P. Nègre, J. F. Devaux, V. Jacob, M. Millerioux, A. Bayle, B. P and R. Prazérès, "Inverse Compton Scattering X-ray source yield optimization with a laser path folding system inserted in a pre-existent RF linac," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 840, pp. 113-120, 2016.

[3] A. Variola, "The ThomX Project," in *2nd International Particle Accelerator Conference (IPAC'11)*, San Sebastian, Spain, 2011.

[4] J. Yang, K. Gen, N. Naruse, S. Sakakihara and Y. Yoshida, "A Compact Ultrafast Electron Diffractometer with Relativistic Femtosecond Electron Pulses," *Quantum Beam Science*, vol. 4, no. 1, p. 4, 2020.

Picosecond Pulse Gating: a New, Extremely Flexible Solution

Picosecond lasers are increasingly used in many applications, whether in the fields of research or in the industrial world. They can be currently found in particular in biophotonics, non-linear optics or even in industrial machining.

IRISIOME Solutions brings to market a laser based on a new method of picosecond pulse generation. The laser architecture, a fully integrated system, is designed to operate under industrial conditions. This offers solutions to many fundamental and applied physics challenges posed to the community of engineers and researchers around particle accelerators.

Among the different series in the IRISIOME SOLUTIONS portfolio, the MANNY systems present unprecedented pulse characteristics in duration, repetition rate, energy per pulse, and beam parameters that will greatly benefit to many processes in the high-energy particles accelerators.

1. Temporal Performances

IRISIOME Solutions laser technology combines the advantages of hyper-frequency electronics and lasers to generate ultra-short laser pulses. This technique involves picosecond pulse gating out of a continuous laser signal using an optical intensity modulator. It is thus possible to achieve pulses ranging from 50 ps up to several nanoseconds having Gaussian, super-Gaussian or Top-Hat profiles, as shown in Figure 4 below. The pulse can be fixed or continuously adjustable.

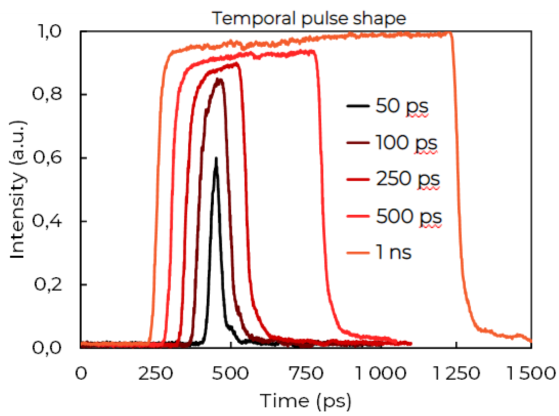

Figure 4 : output pulse of the MANNY from 50 ps to 1 ns

In addition, the pulse rate could also be adjusted to suit user's needs, within a certain operating limit given by the average power and the energy of the pulses.

Even more important, the laser system can be easily synchronized with an external clock facilitating its integration for many applications. Finally, the electronic control of the system allows a mode of operation in pulse packet or "burst" with a flat profile (see Figure 5).

(a)

(b)

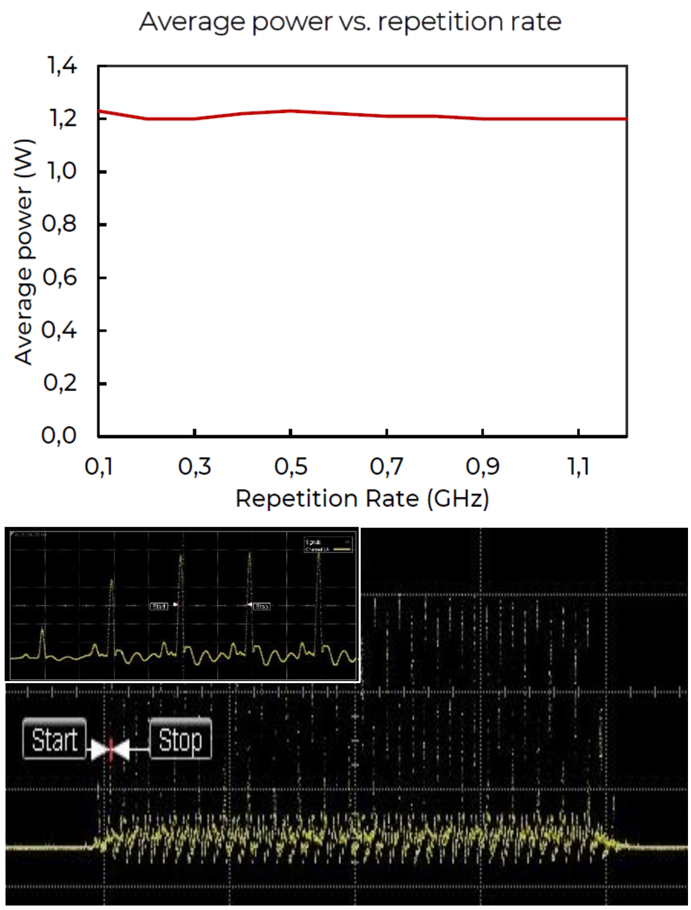

Figure 5: a) Average power of the MANNY as a function of repetition rate b) Example of a burst of ultrashort pulses.

This laser technology is extremely flexible because the rate and pulse duration no longer depend on the laser cavity characteristics (cavity length and amplifier material), but rather on the electrical driving signal and the intensity modulator.

The MANNY laser, turnkey industrial class, offered by IRISIOME Solutions, based on pulse gating allows fine adjustment of the pulse parameters (energy, peak power, rate) with the possibility of synchronizing the laser system with an external signal and, using fiber amplification, delivering up to 30W (amplified master oscillator architecture known as MOPA).

2. Spectral Performances

This technology is perfectly achromatic and can be applied to a wide range of continuous near infrared laser sources. The master oscillator used upstream of the modulators is based on laser diode technology with very high spectral coherence offering a line width of a few megahertz. In addition, fiber amplifier technology makes it possible to benefit from an amplification spectral window covering several tens of nanometers, opening the way to wavelength tunability. Also, the fine wavelength tunability of the master oscillators makes it possible to adapt to solid-state amplifiers already available on the market and widely used in existing installations. IRISIOME Solutions can offer with the MANNY a wide range of Lasers in the near infrared around 1 mm and 1.5 mm then in the visible by second harmonic generation as shown in figure 6.

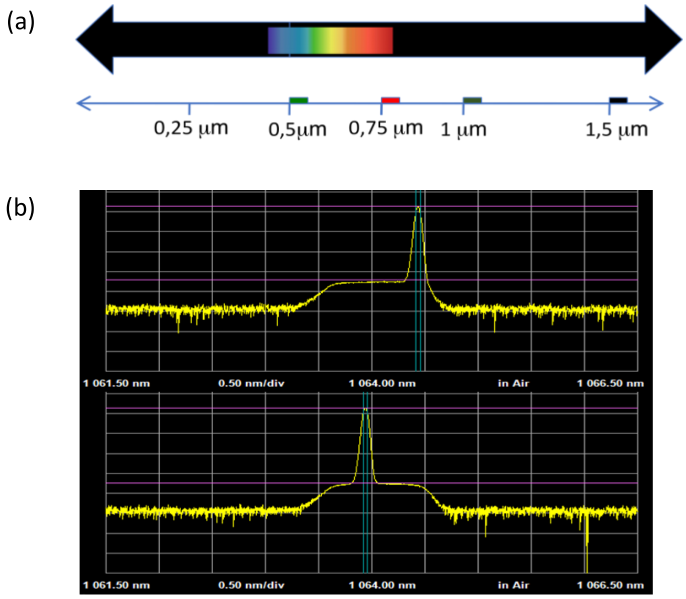

Figure 6 : a) potential wavelength domains of the MANNY from visible to near infrared b) Example of fine tunability near 1064 nm.

3. Energy and Peak Power Performance

The MANNY has the particularity of being very widely adjustable in pulse duration, pulse rate and average power. The technology of fiber amplifiers makes it possible to deliver energies that can reach several millijoules, limited by the amplifier material when the peak power of the pulses will be limited to several hundred kilowatts by the non-linear effects and the confinement of the beam in the fiber core. It is possible to obtain pulses with energies from a few hundred picojoules up to several hundred microjoules. Likewise, the pulse peak power can reach several hundred kilowatts. The graphic below is an example of what the MANNY offers in different versions depending on the pulse rate (Figure 7)

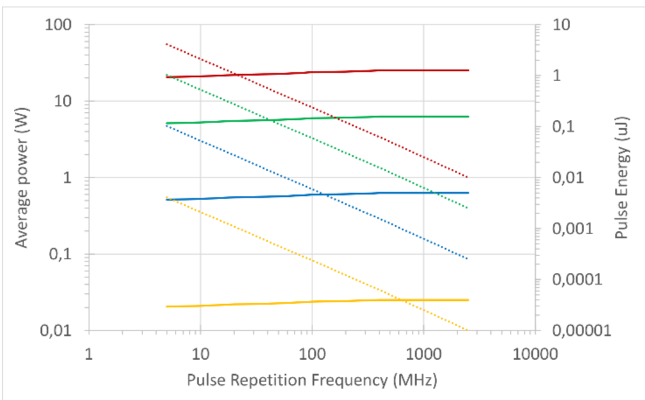

Figure 7 : Example of Energy and average power attained with various MANNY versions.

4. Beam Quality Performance

As presented in the previous parts, the fully fiber MOPA structure confers exceptional optical performance and the technology implemented by IRISIOME Solutions allows great adjustability of the temporal and spectral parameters. In addition, the use of optical fibers for transport and amplification results in a linearly polarized and spatially homogeneous laser beam (Fig 8). Typically, the use of a polarization-maintained single-mode fiber makes it possible to obtain a perfectly Gaussian profile (TEM00) with an M^2 <1.1, a circularity greater than 90% and a polarization rate greater than 20 dB (i.e. 1: 100). These quality parameters are decisive in the laser choice because the laser is placed at the front head of important installations, and often used in complex interactions (frequency conversion, amplification, etc.).

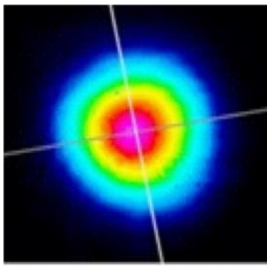

Figure 8 : output beam of the MANNY.

For the highest power levels, the use of large core optical fibers and free-space optics may slightly deteriorate the beam profile and its circularity, but while keeping an M^2 <1.3 and a circularity greater than 85%.

The fully-fiber architecture of the MOPA structure, injected by spectrally well-defined sources, taking advantage of polarization maintaining large core optical fibers allows propagation of high peak power pulses. This enables the best possible solution to these constraints, while ensuring remarkable ease of use.

5. Long-Term Stability

Already several IRISIOME Solutions Laser systems are installed in different centers around the world, in particular at a wavelength close to 1 micrometer.

The integrated optics of IRISIOME Solutions lasers provide the architecture of complete systems with robustness and simplified and minimal maintenance for the initial brick, a major advantage in semi-industrial installations having to operate quasi-continuously.

Another very important point is based on the various controls of operations both in the time domain and in the energy domain. Based entirely on electronic instructions, stability (jitter, synchronization, pulse-to-pulse repeatability, etc.) is almost exclusively based on external parameters and therefore depends on the quality of the control and synchronization electronics.

Irisiome would like to thank Dr. Vincent Le Flanchec (CEA) for his interesting comments and feedback from the use of Irisiome Manny laser, for reviewing the application note and for his improvement suggestions. Irisiome thanks Dr. William Renard for his collaboration in writing this application note.

About IRISIOME

IRISIOME is a French startup company from Bordeaux, in France founded in 2015, The Company is the result of a valorization project led by the CELIA Laboratory (Centre Lasers Intenses et Applications) that was aiming at developing a user friendly and simple laser source for medical applications. Since the beginning of the project our team has strengthened its expertise by developing an innovative laser architecture, which would be easily integrated in any experiment or system.

Willing to widen its offer and confront its laser sources to challenging applications, **IRISIOME** has created a new brand, **IRISIOME Solutions,** fully dedicated to the scientific and R&D markets. To be able to fulfill our users' specific requirements, we are making ourselves available to take up any challenge and new developments that will push our systems to the highest level of performance.

For more information, you can visit our website (http://www.irisiome-solutions.com) or contact us at contact@irisiome-solutions.com