

Ultra-short laser pulses for novel particle accelerators

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Abstract – Novel particle accelerators are profiting from compact and high power lasers for beam generation or high gradient acceleration. Moreover, high brightness electron beams colliding with photons have paved the way to generate coherent X-ray radiation. Here we review the basic mechanism behind the generation of ultra-short high power laser system and in particular we report on laser beam characterisation at FLAME and STRATCLYDE, useful for particle acceleration driven by plasma. Eventually we discuss on the applications currently developed or under design at INFN-LNF in the frame of SPARC_LAB.

I. HIGH POWER, ULTRA-SHORT LASER SYSTEM

The development of Chirped Pulse Amplification (CPA) has to be credited to Strickland and Mourou [1]. This technique has given the possibility to produce high peak powers from lasers through amplification of very short (femtosecond) laser pulse energies previously available only from long-pulse lasers. The idea of CPA is simple and beautiful at the same time: given the damage-threshold limitations encountered by ultra-short laser pulses while propagating through the laser amplifier, the ultra-short pulse will be manipulated in a controllable and reversible fashion so that the laser amplifier never encounters a short, high power pulse, and only the laser system components compatible with such high peak powers will be exposed to it.

The CPA technique is based on the idea of using reversible manipulation of the temporal characteristics of

ultra-short laser pulses. An ultra-short laser pulse is firstly stretched in time introducing a frequency chirp in the beam; this is done using a pair of diffraction gratings arranged so that the low-frequency component of the laser pulse travels a shorter path than the high-frequency ones.

After passing through the grating pair, the laser pulse is much longer (typically 100-200 ps) than the original by a factor of 10^3 to 10^5 . After this operation, the pulse now has an intensity sufficiently low compared with the intensity damage limit of gigawatts per square centimetre for optical components, and, therefore, can be safely introduced into the gain medium and amplified by a factor 10^6 or more.

Finally, the amplified laser pulse is recompressed back to the original pulse width through the reverse process of that used for stretching, that is, a grating pair introduce a frequency chirp to the beam of equal magnitude but opposite sign to the one introduced at the stretcher. The final output pulse is therefore of high energy and ultra-short duration with peak power many order of magnitude higher than that achievable before the invention of CPA. Using this technique the today laser systems can reach the petawatt power.

Here we will present the significant measurement that can be performed on a CPA laser system and in particular we refer to two systems, FLAME and ALPHA-X and we will give an overview of the possible applications, within the SPARC_LAB frame, of these kind of laser systems.

II. SIGNIFICANT MEASUREMENTS ON A LASER BEAM

In this section, we will describe the measurements that can be performed on a high power laser system. In particular we refer to two CPA laser systems, FLAME which is situated in Frascati, at INFN, and ALPHA-X, which is situated in the University of Strathclyde, in UK. The main difference between the two laser systems, is the peak power: in fact, while ALPHA-X has a peak power of 30 TW, FLAME reaches a peak power of 250TW. As we will see in this section, the difference in peak power is not due only to a higher energy, but also a big difference in the laser pulse duration.

In order to constantly check the laser status, there are many different laser diagnostics: some of those are used as a daily procedure and some are used periodically. The main measured parameters are performed on pulse length, spot size, energy, power, bandwidth, contrast and phase front.

The first daily diagnostic is the laser power meter to read the oscillator output power. It is very important to take this measurement every day because a drop of power in this point will cause a drop of power in the whole laser chain.

The energy of the laser is also measured every day at some key points in the laser chain: at the output of each amplifier, before and after the compressor. Any energy drop requires a check of the alignment and a clean of the optical components.

Another important diagnostic is the laser spectrum before the final amplifier: this measurement will give information on the laser spectrum shape and bandwidth. A typical laser spectrum recorded on the ALPHA-X laser system is shown in fig. 1.

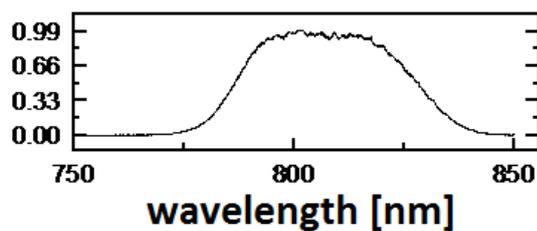


Fig. 1: typical laser pulse spectrum from the ALPHA-X laser system before the final amplifier.

The central wavelength of the laser is around 810 nm, the spectrum bandwidth is 35 nm and the spectrum is flat top. The spectrum can easily drift in band and the farther it is from 800 nm, the worse will be the transmission in the laser chain. Also, it is fundamental to have a flat top spectrum: a hole in any part of it, will make the pulse to behave like a double beam and lot of non linear process can happen. Also, it is crucial that the spectrum is broad: the broader is the spectrum, the shorter will be the final

laser pulse.

To ensure the flatness of the laser bandwidth, an optical component called "dazzler" is used. A dazzler is an acousto-optic modulator capable of shaping spectral phase and amplitude of ultra-short laser pulses. It is a programmable spectral filter which uses travelling acoustic wave to induce variation in the optical properties thus forming a dynamic volume grating.

In particular, in FLAME, there are two acousto-optic modulators, one is the dazzler and the other is called "mazzler". In this case, the dazzler is used only to shape the spectral phase, while the mazzler is used to shape the spectral amplitude of the laser pulse. Using these two devices at the same time, it is possible to have a much larger laser spectrum (as shown in fig. 2) and therefore it is possible to achieve shorter pulses.

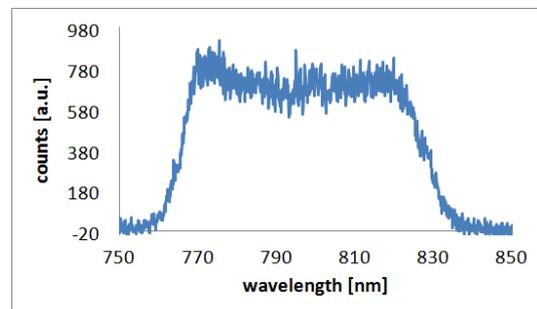


Fig. 2: typical laser pulse spectrum from the FLAME laser system before the final amplifier.

The latest daily measurement is the phase front of the laser beam. In the FLAME laser chain, at the exit of the compressor, there is a particular mirror, called "adaptive optics", which is a deformable mirror that is made by a dielectric thin mirror which has 52 step motors on the back; an image of this optics is shown in Fig. 3.

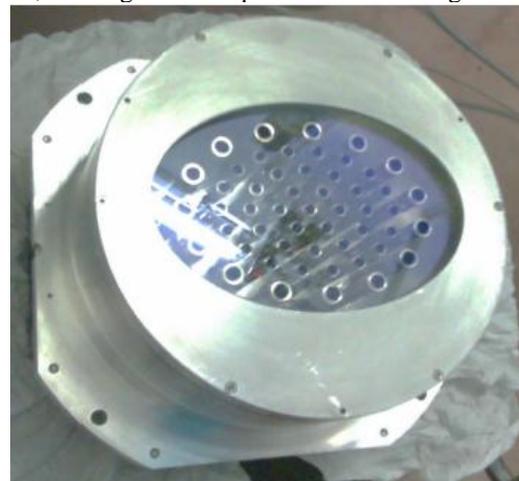


Fig. 3: Photography of the FLAME adaptive optics.

The motors placed on the back of the mirror, can be moved in order to shape the phase front of the beam so to have a perfect spherical front. The measurement is done on a loss of a mirror which is then focused on a phase front sensor. In order to measure the phase front, each motor placed on the back of the mirror is moved and an image of the phase front is recorded. After all the motors have been moved, a matrix of response is available, and it can be used to shape the phase front in the desirable way.

Fig. 4 shows two images of phase front measurement: the one on the left side, is the phase front measured without any correction which shows lots of aberrations (the rms error respect to a perfect spherical phase front of about 2 micron) and the one on the right side shows a corrected phase front which shows almost no aberrations (the error this time is only 50 nm).

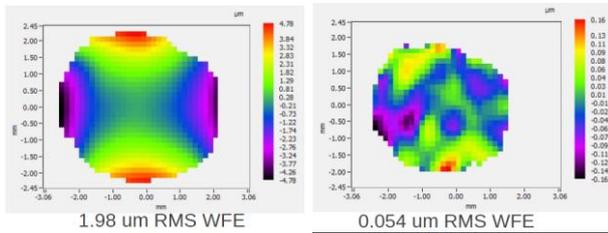


Fig. 4: Phase front error measured (a) before phase front correction and (b) after correction showing an rms error respect to a perfect spherical phase front of (a) 1.98 micron and (b) 0.054 micron.

The importance of this kind of measurement is that a wave front with a small error respect to a perfect spherical wave front has a better focusability.

The first of the occasionally applied diagnostics is a SPIDER for measuring the pulse duration. SPIDER is a spectral interferometer that uses two interfering pulses to reconstruct the temporal pulse shape. This diagnostic is used after the compressor. A typical pulse duration measurement - showing a full width half maximum pulse length of 23 fs - is shown in fig. 5.

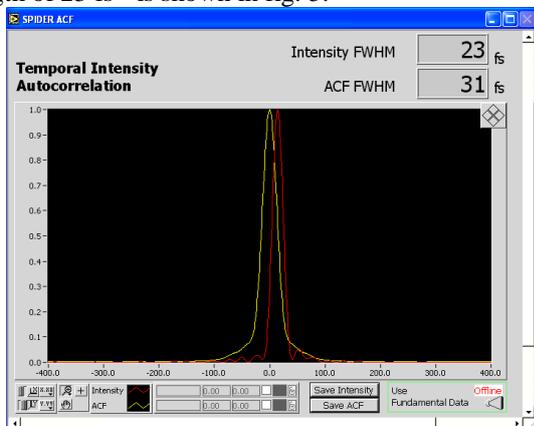


Fig. 5: typical laser pulse duration from the FLAME laser system at the exit of the compressor.

Another periodical measurement is the amplified laser beam profile at the interaction point. This is a very important measurement because a high quality focal spot with maximum energy in the central region is desirable for most of the experiments. In particular, fig. 6 shows a focal spot for the FLAME laser. The beam is imaged inside the interaction chamber using a Flay CCD camera with a microscopic objective to have a magnification of the spot. The parameters that can be extrapolated from this image, are the beam size and shape and the energy contained in the main spot (here we refer to the spot diameter $1/e^2$).

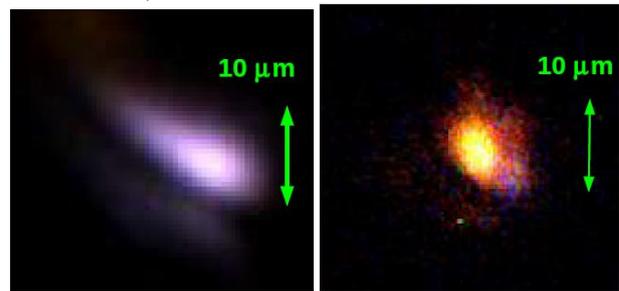


Fig. 6: FLAME focal spot (a) without phase front correction and (b) with phase front correction.

As we can see, for these particular measurements, the beam, which is focused by a 1 m focal length parabola, is very oval in the case of no phase front correction and becomes very round when the best phase front is applied. Moreover, we can clearly see that the use of the adaptive optics is crucial also for the energy contained in the central spot (considering the $1/e^2$ diameter): when there is no phase front correction, the energy inside the central spot is only 25% while after the phase front correction, this energy goes to 60%.

The last periodical measurement, is the contrast ratio, which is defined as the difference in intensity between the main femtosecond pulse and pre- and post-pulses and pedestals on the picosecond and nanosecond timescales.

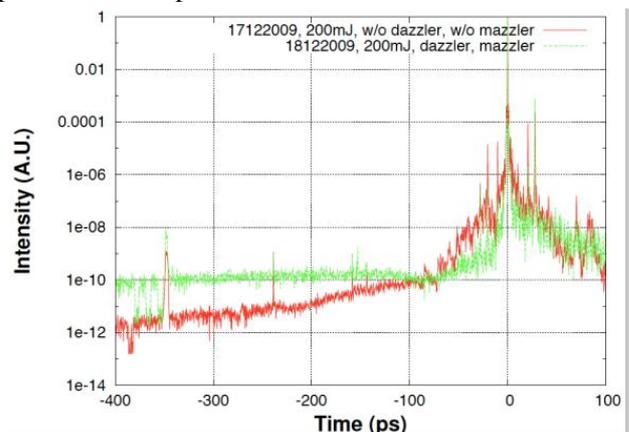


Fig. 7: typical contrast ratio measurement from the FLAME laser system.

This measurement is performed with a SEQUOIA that is a commercial high dynamic range third-order femtosecond cross-correlator developed by Amplitude Technologies. Fig. 7 shows a typical contrast ratio measurement, showing a contrast of 10^{10} . The higher is the contrast ratio, the better is the laser performances (moreover when using the laser to perform plasmas, when pre-pulses can cause a pre-ionisation that is absolutely undesirable).

III. APPLICATIONS TO PARTICLE ACCELERATORS

High power, short duration laser systems, are used in a wide range of applications. Here we will focus in particular on those implemented (or under design) in LNF in the frame of SPARC_LAB.

Fig. 8 shows the layout of the SPARC and FLAME bunkers.

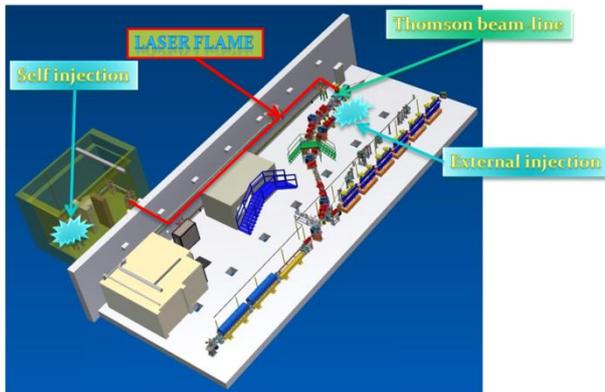


Fig. 8: FLAME and SPARC bunkers.

As shown in fig. 4, SPARC_LAB is composed of two bunkers: one is the FLAME bunker, which is dedicated to the "laser only" experiments, and the second one, the main one, is the SPARC bunker, where the laser is coupled with the SPARC conventional accelerator.

As shown in the bunkers layout, the FLAME laser can be used for many experiments, and in particular here we will focus on laser-plasma acceleration by self-injection, external injection, proton acceleration by thin metal target and Thomson scattering.

The first application is probably one of the most challenging and in literature is referred to as Laser WakeField Acceleration (LWFA). This acceleration technique was proposed in 1979 by Tajima and Dawson and is based on the concept of plasma and plasma waves. The role of the laser in this scheme, is firstly to ionize a gas and then to displace the plasma electrons so to stimulate plasma waves thus to accelerate electrons. These acceleration schemes have been largely studied around the world (and in LNF as well) and have demonstrated that the accelerating fields reachable with this technique is extremely high and can exceed the

100GV/m, which is several order of magnitude higher than that reachable with conventional accelerators; this means that the scale length of plasma accelerators are incredible small and GeV electron bunches can be (and have been) produced in a few centimetre. The physics is very complicated, but the principle of work can be easily explained by the well known example of the boat on the sea.

Fig. 9 shows a speedboat travelling on the sea and on the back there is a surfer. Like a speedboat leaving a wake that a surfer can ride, a laser pulse in a laser-plasma wakefield accelerator creates a wake in the plasma that an electron beam "surfs" to high energy. The ridges at bottom right are the laser pulse, which drives the wake as it speeds through the plasma.

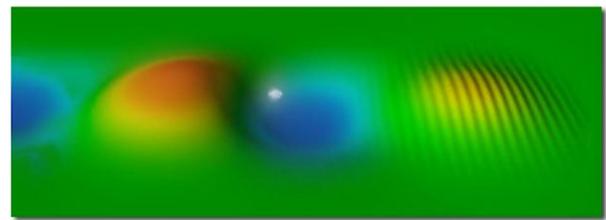


Fig. 9: Principle of work of LWFA [3].

This accelerating technique is very promising because of the compactness of the accelerators; however, the quality of electron beams from LWFA is not yet comparable to that accelerated by conventional accelerators and for this reason an enormous research is undergoing in this field.

There are several possible schemes that have been proposed to overcome this problem; one of them is the so-called external injection, which employs the high quality electrons bunches accelerated conventionally and the high accelerating gradient reachable with plasmas to further accelerate the electron bunches while preserving the high quality. In this particular case, the role of the laser beam is to fully ionize the gas and drive the plasma waves.

The principle of work of this accelerating technique (as shown in Fig. 10) is very similar to that of laser wakefield acceleration, a part from the fact that there is no trapping of electrons by self-injection. This means that, in this case, the laser has a sufficiently high energy to ionise the plasma and drive the plasma waves, but not enough to trap the electrons on the back of the bubble.

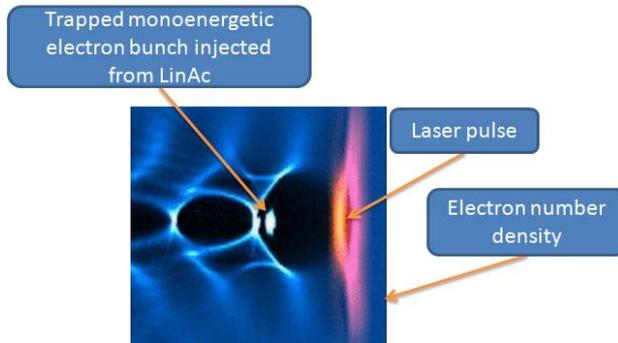


Fig. 10: Schematic of the external injection [4].

The major challenge of this novel acceleration technique is the synchronisation between the laser pulses and the electron bunches which needs to be as synchronous as few tens of femtoseconds (which is the laser length) so to be able to place the electron bunch on the accelerating part of the plasma wave.

Another application is the so-called "Target Normal Sheath Acceleration", which is one of the experiments that can be performed with a laser system requiring the highest laser beam performances.

Fig. 11 shows a schematic of this acceleration technique.

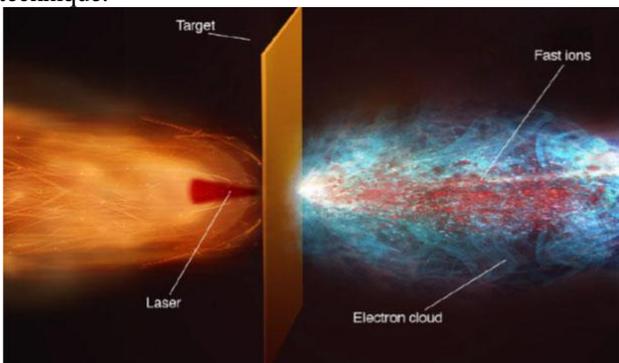


Fig. 11: Schematic of proton acceleration through Target Normal Sheath Acceleration [5].

The high power, ultra-short laser pulse is focused by a short focal length parabola on the front of a thin metal sheath. The interaction of the laser beam with the metal target, give rise to a plasma on the surface of the target, inducing a high charge separation. Due to this charge separation, electrons will be accelerated and forced to travel through the rear of the target, where they stop and give rise to a high electrostatic field, capable of ionising fast the atoms and accelerate the ions that are on the rear of the target. In this scheme, the electrons are used as an intermediate step to transfer the energy from the laser to the ions.

Finally, another application is Thomson scattering, which is the scattering due to collision between electrons

and photons. The principle of work is very similar to that of a free-electron laser, where the electrons are forced to wiggle on a sinusoidal path by an array of dipole magnet with alternate magnetic field (called undulator). In this case, the undulator is the laser beam (an electromagnetic wave) which is counter propagating to the electron beam.

The layout of the final focus and interaction chamber of the Thomson scattering beam line is shown in Fig. 12. The electron beam travels from the left to the right, while the laser beam comes from the top left, goes on the 1m focal length parabola and then travels from the right to the left (counter propagation).

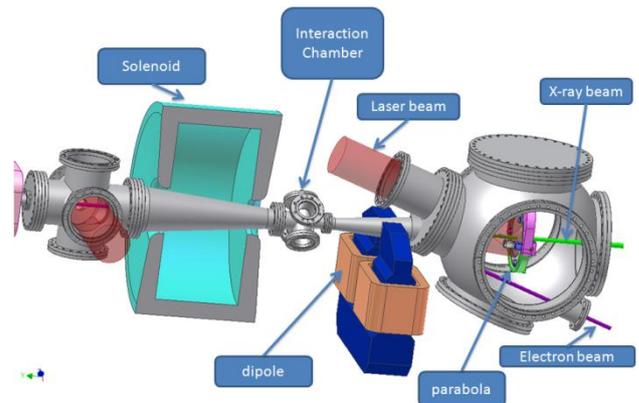


Fig. 12: Thomson scattering interaction chamber.

The interaction chamber, which is the 6 way chamber placed between the parabola and the solenoid, represent the point where both the electron beam and the laser beam are focused and it is the point where the radiation (x-ray) is produced.

IV. ACKNOWLEDGMENTS

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