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First electrons from the new 220 TW Frascati Laser for Acceleration and Multidisciplinary Experiments (FLAME) at Frascati National Laboratories (LNF)

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ABSTRACT

A new era of laser based plasma accelerators is emerging following the commissioning of many high power laser facilities around the world. Extremely short (tens of fs) laser pulses with energy of multi-joules level are available at these newly built facilities. Here we describe the new 220 TW FLAME facility. In particular we discuss the laser system general layout, the main measurements on the laser pulse parameters, the underground target area. Finally we give an overview of the first results of the Self-Injection Test Experiment (SITE), obtained at a low laser energy. This initial low laser energy experimental campaign was necessary for the validation of the radio-protection shielding (Esposito, 2011 [1]) we discuss here. With respect to our preliminary configuration, with a pulse duration of 30 fs and a focusing optic of F/15, we discuss here the minimum laser energy requirements for electron acceleration and the forward transmitted optical radiation.

1. Introduction

The invention of Chirped Pulse Amplification (CPA) technique [2] has revolutionized the field of laser plasma interaction studies. This technique paved the path for the development of high power laser systems that can now be built on a small scale and hence led to an exponential growth in laser matter interaction studies. Laser-based particle accelerator [3,4], bright and ultrafast X/γ-ray sources [5] have reaching exciting results in the past few years. In particular new methods to control injection [6,7] and to produce ultrashort and collimated X/γ-ray beam [8,9] enhanced the interest in newly built laser facilities able to deliver from TeraWatt to PetaWatt laser pulses with relatively high repetition rate (10–1 Hz). Moreover the possibility to use in conjunction such laser systems with electron bunches from a LINACs is giving new thrust to Thomson scattering based X-ray sources [10].

The commissioning of the FLAME laser laboratory at *Laboratori Nazionali di Frascati—INFN* is aiming at this direction, providing facility which can deliver very intense and up to 220 TW laser pulses that can be used in conjunction with the SPARC LINAC. The FLAME laboratory is now fully assembled, the Clean Room hosting the Laser system (recently commissioned) with the control-command, the laser-beam transport line, the radio-protection shields and the Flame Target Area for laser gas-jet interactions. Actually a laser-plasma electron acceleration, the so-called Self Injection Test Experiment (SITE), is in progress to assess the overall performance of the facility and to deliver the first scientific results on laser-plasma acceleration. The first result using the minimum

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laser energy required for self-injection was used to obtain an initial dosimetry measurement for the validation of the radio-protection measures described elsewhere [1]. These preliminary data show that control of the main laser parameters at the target position has been achieved, including the off-axis parabola focusing, pulse duration and beam pointing. A general description of the FLAME facility will be given along with a summary of the first low energy results obtained in 2010.

2. The facility

A layout of the FLAME laboratory is shown in Fig. 1, in which three different zones can be identified: the first (white) is a free access zone that holds the Control Room, the second one (red) shows the Clean Room (or Laser Room) that contains the FLAME laser system. Finally the third zone (blue) is an underground bunker divided in two zones, one (right) for the laser pulse compression and diagnostic and another (left) hosting the target interaction chamber. The two areas are separated by a radio-protection wall labyrinth. A scheme of the laser-plasma accelerator with one photo of the internal view of the interaction chamber is also shown. After the compressor the beam can be sent alternatively in two different beam lines output: one is used to send the beam in the Flame Target Area and the other one to send the laser pulse in an adjacent bunker where the SPARC LINAC is placed. In this way it is possible to use the laser beam for all-optical setup (as for SITE) or for LASER-LINAC experiments.

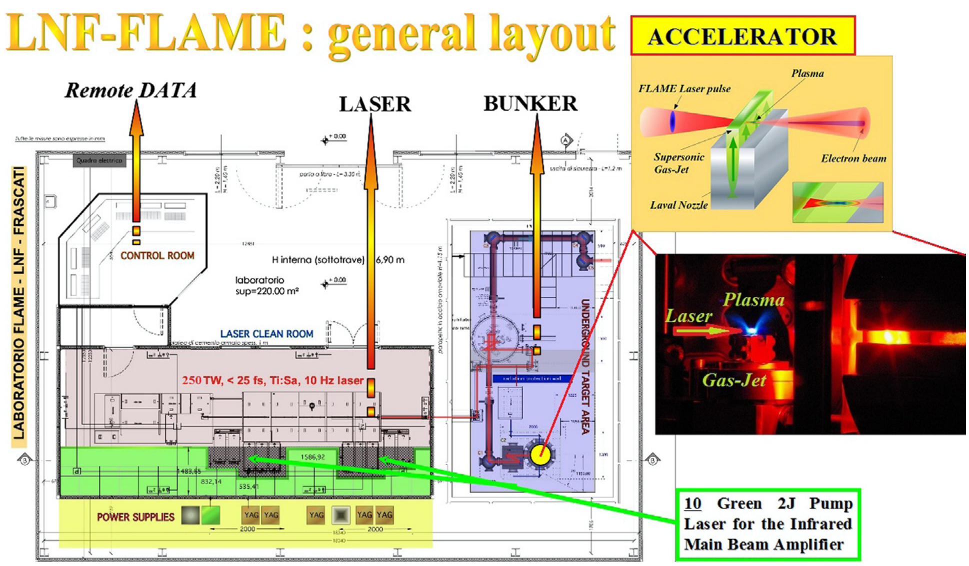

Fig. 1. Layout of the FLAME laboratory, three different zones are visible, the free access zone (white), the Clean Room containing the FLAME laser (red), the 6 m underground bunker (blue), and a scheme reproducing the laser-plasma accelerator with an internal view of the interaction chamber. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

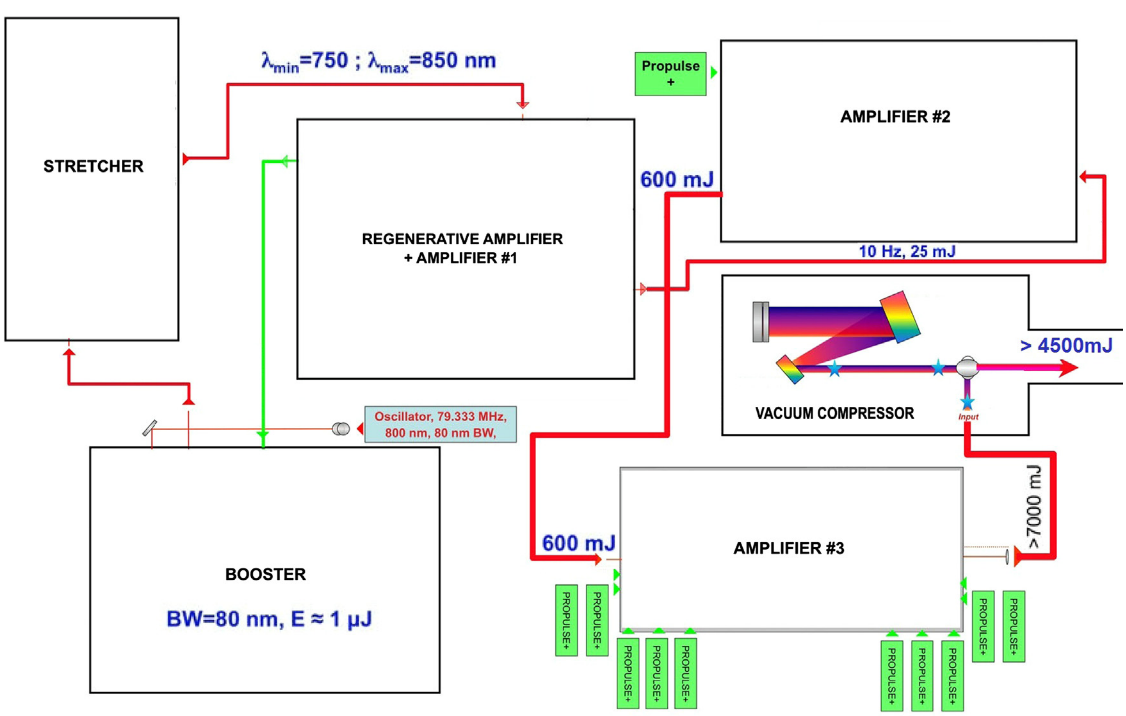

Fig. 2. Layout of the 220 TW FLAME laser system.

3. The FLAME laser

The FLAME laser, placed inside a temperature and humidity stabilized Clean Room, is based on a CPA scheme that delivers up to 220 TW laser pulses at 10 Hz repetition rate. As it is shown in Fig. 2 the system includes a front-end with pulse contrast enhancement (booster), bandwidth (MAZZLER) and spectral phase (DAZZLER) control at the regenerative amplifier level that yields pulses with 0.7 mJ in 80 nm bandwidth. These pulses are then further amplified by the first amplifier to the 25 mJ level while the second amplifier brings the energy to the 600 mJ level. Here a 10% of the energy is picked up to be used as Auxiliary beam for interferometry in the SITE setup. The third amplifier is based on Ti:Sapphire crystal pumped by 10, frequency doubled Nd:YAG laser pulses for a total of up to 20 J of energy at 532 nm. In this case a cryogenic device is utilized to cool down the main Ti:Sa crystal: in this way the enhanced thermal conductivity of the crystal enables a better extraction of the heat due to the pump energy in the crystal, strongly reducing thermally induced phase-front distortion. The extraction energy is as high as 35%, leading to a final energy in the stretched pulses in excess of 7 J (best test 7.4 J). The pre-pulse contrast level was measured to be $>10^{10}$ at sub-ns range.

4. Laser diagnostic and parameters

The main parameters of the laser pulse are measured by using specific diagnostics, mainly the pulse energy, duration, contrast and the Strehl ratio. The pulse energy is typically measured by using a calorimeter after the main cryogenic amplifier (MP3) and the final energy at the interaction point is evaluated by using the total efficiency transmission measured at low power (about 63%). In Fig. 3 a long term full energy stability test on the 10 Hz laser pulses is shown, measured inside the Laser Room at the exit of the cryogenic amplifier, in this energy level condition the Strehl ratio was measured to be about 0.35. The pulse duration is measured by a SPIDER diagnostic: this device gives in a single shot the measure of the spectral phase that is essential for the optimization (performed by the DAZZLER) of the pulse duration below 40 fs that in principle can be optimized down to 20 fs. In Fig. 4 (left) the measurement of the duration of an optimized pulse of about 23 fs (FWHM) obtained on the Auxiliary beam is shown, similar results (26 fs) were measured at full energy on the Main beam, and (right) the pulse contrast measured by SEQUOIA diagnostic on a sub-ns time scale is of the order of 10^{10}.

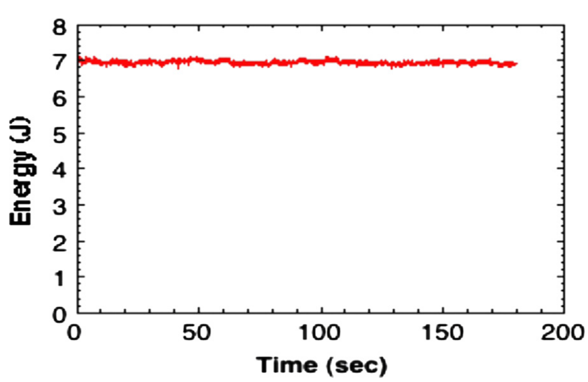

Fig. 3. Full laser energy stability test.

5. Flame bunker

After the main amplifier the pulses are sent out of the Clean Room through an anti-reflection coating window. Pulses, still traveling in air, are transported up to the vacuum compressor placed in the underground bunker. Once compressed, the pulse is transported under vacuum to the target chamber via remotely controlled beam steering mirrors. In Fig. 5 the Flame bunker layout is shown, the compression/diagnostic zone and the Flame Target Area with the basic scheme for SITE are visible.

6. First electrons from SITE

This laser-plasma electron acceleration experiment has been conceived as a test of the laser performances and, in a first phase, to explore the minimum laser-energy required for self-injection and acceleration of the particles, in order to obtain an initial dosimetry measurement for the validation of all the radio-protection shielding scheme (described elsewhere [1]). The final goal of this Self-Injection Test Experiment (SITE) is to use the full power FLAME laser pulses to achieve GeV level electron acceleration in about 4 mm as described elsewhere [11]. In the first phase of SITE accelerated electron bunches were obtained from the interaction of the femtosecond laser pulse with a nitrogen supersonic-gas-jet working with a back pressure of about 17 bar and a laser-intensity of 2×10^{18} W/cm^2. These preliminary data show that in our conditions (F/15), at fixed pulse duration of

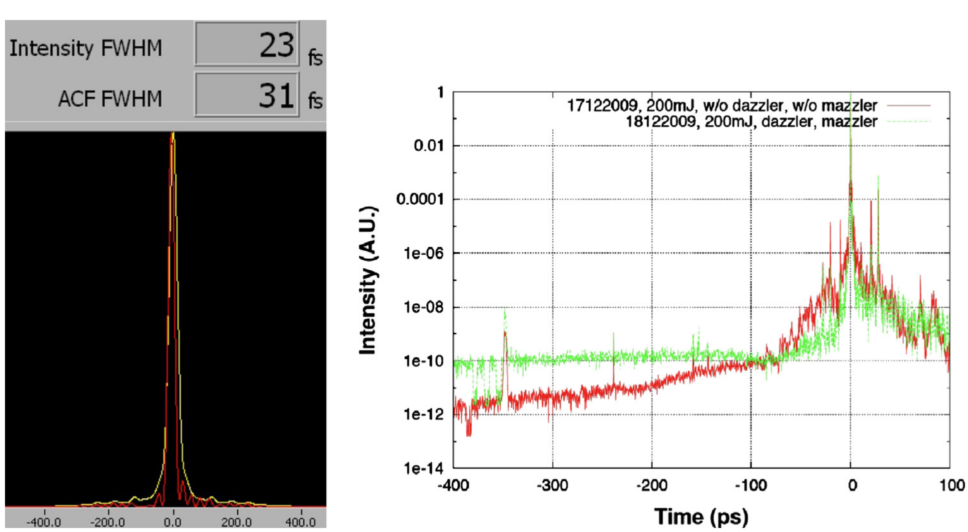

Fig. 4. (left) Optimized Auxiliary pulse duration of 23 fs (FWHM) and (right) sub-ns time scale pulse contrast on the order of 10^{10}.

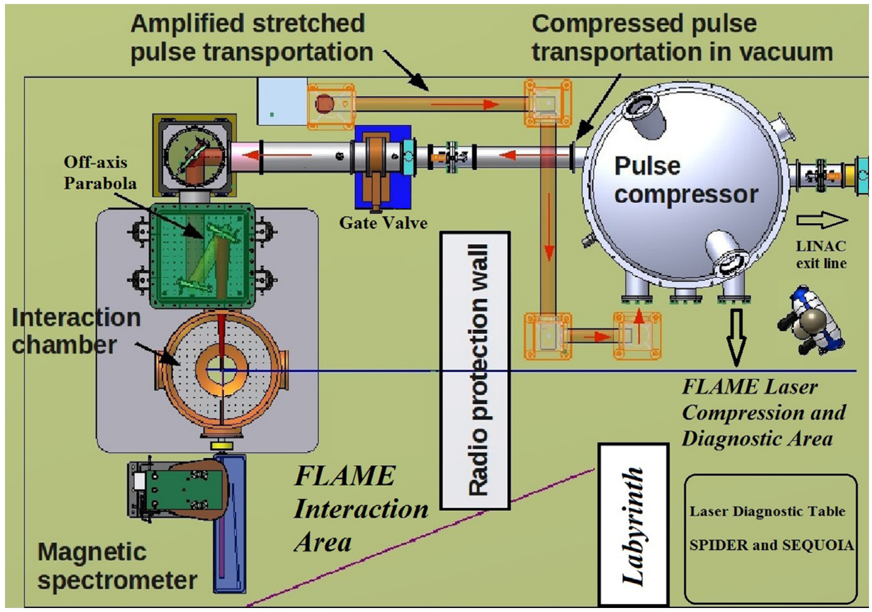

Fig. 5. Flame bunker layout: zone 1 (right) compressor and laser diagnostic and zone 2 (left) Flame Target Area with basic scheme for SITE.

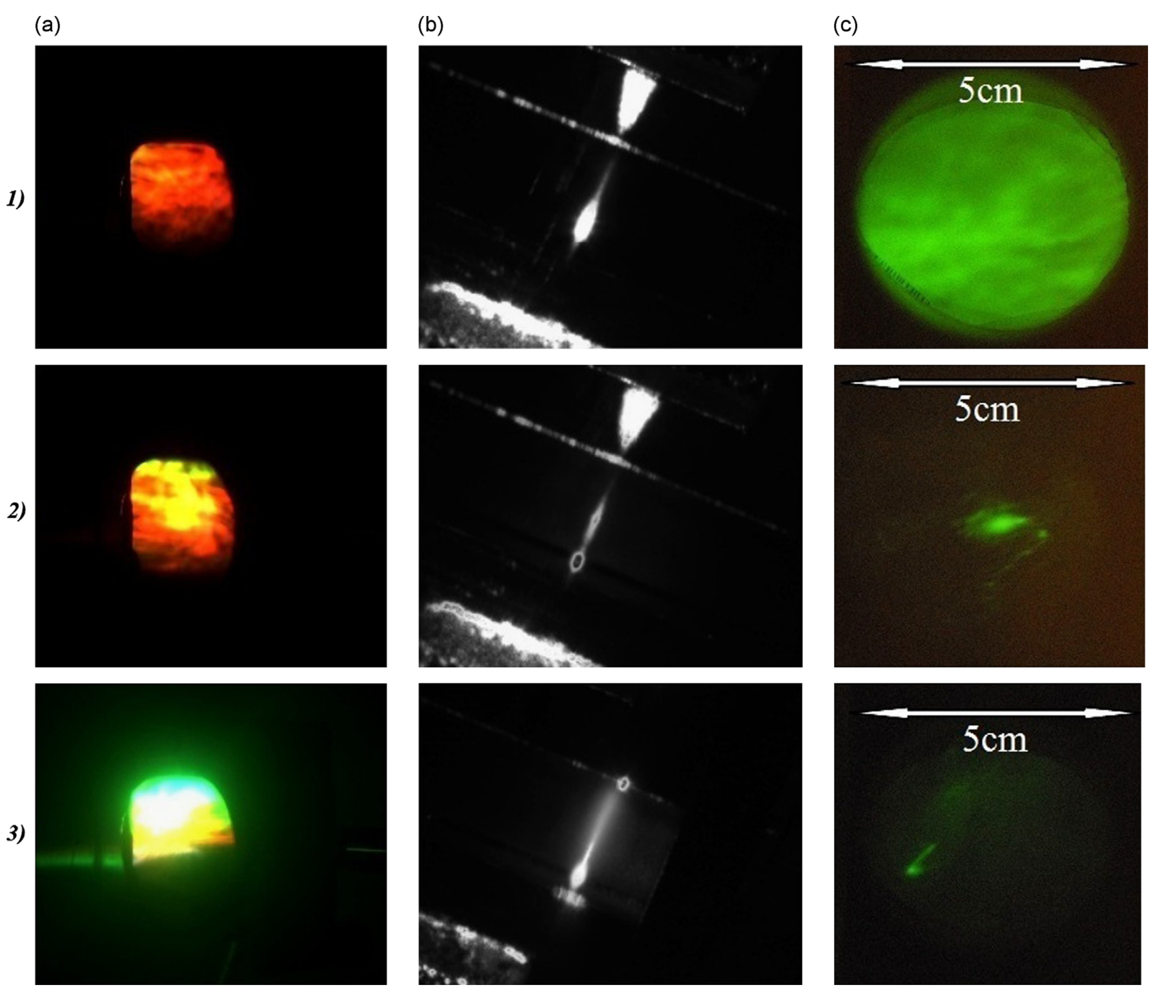

Fig. 6. First obtained results (see text for description).

about 30 fs and over a minimum energy per pulse of about 300 mJ, collimated (10 mrad) electron bunches can be obtained. Here we only qualitatively describe some different interaction condition obtained at this low laser energy level. Fig. 6 shows some representative results from the different diagnostic, in particular in column: (a) the forward transmitted laser light impinging on a diffusing screen, (b) the Thomson-side scattered laser light, and (c) the scintillating Lanex screen that is placed on the path of the accelerated electron bunches. The different rows refer to different degrees of collimation obtained during the experimental campaign: (1) no-collimation (>100 mrad angle of emission), (2) medium collimation (30 mrad), and (3) high collimation (10 mrad). The case in row (1) shows the possibility to irradiate a large area (cm scale) in one shot and is well suited for biological applications were large sample must be irradiated. The case in row (3) corresponds to the condition in which a proper accelerating structure (the so-called bubble) self-injects and accelerates only a selected bunch of electrons. This is the condition described in details in Ref. [11] and is expected to lead to peak energies close to the GeV at full laser power.

The case in row (2) is intermediate between (1) and (2). In the column (a) and starting from the case (1) it is possible to qualitatively observe an increasing blue-shift going toward the case (3) in the forward transmitted light. As confirmed in subsequent measurements stronger blue-shift correspond to higher energy in the accelerated electrons bunches.

7. Conclusion

A general overview of the FLAME facility is given, including the different laser stages up to the last amplifier and the under vacuum compressor. A description of the bunker, is also given of the set up of the laser-plasma experiment SITE (Self-Injection Test Experiment) conceived also as a test of the laser performance and for the commissioning of the entire laser facility. The first result on the acceleration of electron at low laser energy level is shown with a description of three different acceleration conditions affecting the final divergence of the accelerated electrons. The radio-protection shielding was successfully tested during this first experimental phase of the commissioning and the detected radiation dose was not distinguishable from the background level one.

Further tests at full laser power and GeV-level electrons energy were successfully performed very recently and will be described in deep elsewhere.

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