Research activity in the laboratory for inertial confinement fusion in ENEA - Frascati

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Abstract. Research on the use of nuclear fusion for energy production is carried out at ENEA mainly in the Frascati Research Center with laboratories dedicated to the study of magnetic confinement (Tokamak FTU) and inertial confinement (ABC). This paper summarizes the ongoing experimental programs and diagnostic development related to the studies of laser produced plasmas.

1. Introduction
The laboratory for inertial confinement fusion is dedicated to the study of laser produced plasmas in the 2 beams laser facility ABC, which can deliver up to 200 J in pulses a few nanoseconds duration. The system is suitable for irradiating planar targets at I >1014 W/cm² allowing to access intensity regimes close to the requirements of fusion targets. Present ABC experimental programs are dedicated to the investigation of transmission properties of porous materials and to the study of a-neutronic fusion reactions and to the analysis of electromagnetic pulses accompanying the laser-target interaction.

Porous materials, such as polystyrene foams, have been proposed as random absorbers of radiation in laser plasma experiments; their capability of homogenizing the energy transferred from the laser to the target is particularly interesting for inertial confinement experiments, in order to limit the onset of instabilities, which can downgrade the implosion gain. The average densities of the foam absorbers used were larger than the critical density at the laser wavelength; in these conditions absorption is mainly distributed on the absorber’s volume.

A-neutronic fusion reactions in solid targets irradiated by laser are also studied. Using plastic targets doped with Boron we got an appreciable number of counts of α particles at the laser powers available in ABC, indicating the occurrence of p + 11B = 3α reactions. Similar experiments were also conducted in collaboration with the picosecond laser facility LULI (Laboratoire pour l’Utilisation de Laser intense – Ecole Polytechnique, Palaiseau). In order to better understand these effects it is necessary to study the behaviour of fast particles escaping the plasma, for this purpose diagnostics such as Thomson parabolas and time of flight detectors have been employed.

Electromagnetic pulses generated in the interaction of fast laser pulses with matter can be relevant since they can produce high current noise capable of disturbing signals and damage instrumentation. An analysis of these effects has recently been started in ABC.

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2. The ABC installation
The main beam parameters of the ABC laser (Fig. 1) are reported in Table I.

![Figure 1. The ABC laser facility.](image)

| Parameter                | Value                                      |
|--------------------------|--------------------------------------------|
| **Active medium**        | Glass Neodimium Phospate                   |
| **Wavelength**           | 1054 nm                                    |
| **Beam energy**          | ≈ 2*100 J                                  |
| **Pulse duration**       | ≈ 2-5 ns                                   |
| **Max power/beam**       | ≈ 50×10^9 W                               |
| **Rising time**          | ≈ 1 ns                                     |
| **Rod diameters**        | Ø 10/20/50/75 mm                           |
| **Output beam diameter** | ≈ Ø 75 mm                                  |
| **Intensity**            | ≈ 10^{13} – 10^{15} W/cm^2                |
| **Minimum focal spot**   | ≈ 40 μm                                    |
| **Beam integrator**      | Induced                                    |
| **Space Incoherence**    | 500×500 μm                                 |

The focusing optics is characterized by large aperture, short focal length lenses (f/1, f=10cm) (fig. 2) and the possibility of using Induced Space Incoherence integrators (Fig.3) to smooth the beam profile.

![Figure 2. The focusing lenses on the target.](image)
3. Diagnostics

3.1. Radiation and particle diagnostics

A wide set of diagnostics is used for the measurement of the radiation and particles emitted by the plasma. Faraday cups at 10 different angles to the target perpendicular obtain time of flight analysis of the ions emitted by the plasma. Diamond detectors are also used for time of flight analysis, being scarcely affected by electromagnetic noise they offer a better response to fast particles, which are detected in the early phases of the discharge. The time response of diamond detectors depends on the sensor’s dimension and structure, Fig. 4 shows the 2 detectors used in ABC with related signals. Ion analysis can also be performed with Thomson spectrometers, which allow ion discrimination. A 4-pinhole X ray camera is producing 4 plasma images on a microchannel plate detector through Be filters which select different energy bands. A time resolved set of X ray images can also be produced on gated X-ray camera Kenntech slix 4.

Figure 3. Beam smoothing by ISI plates, showing the different beam waist profiles obtained.

Figure 4. Two diamond detectors used in ABC: (top) High Purity Single Crystal Diamond SCD464650D (Diamond Detectors Ltd); (bottom) Diamonds with Interdigital Structure (Tor Vergata University, Rome).
Optical diagnostics for plasma self-emission include a visible streak camera with 200 ps resolution, and spectroscopy. Shadowgraphy and interferometry of the plasma are performed by use of an optical probe beam originating from the main beam and duplicated in frequency, examples are shown in Fig. 5.

Figure 5. Interferogram and analysis of a laser produced plasma in ABC.

4. Experimental programs

4.1. Study of porous materials as absorbers of laser radiation

Foams of low-density materials were irradiated in ABC to study their behaviour in the ablation process. The use of foams with initial density greater than the critical value for the laser wavelength can be beneficial in compression experiments by distributing the input energy more uniformly, thus reducing the onset of hydrodynamic instabilities. The homogenisation is due to the formation of small plasma cells inside the volume of the porous material. In the most recent experimental campaign the energy absorption of Polystyrene foams with densities in the range 10-60 mg/cm$^3$ was measured by depositing the foam specimen on thick Aluminum substrates. The high pressure shock wave, originated at the ablation front and reaching the substrate, melts and evaporates a volume of matter $V_{crater} = \frac{\sigma K_p E_L}{\alpha w_0 \rho_0}$, which can be assumed as a measurement of the foam transmission efficiency $\sigma K_p$. ($E_L$ = Energy of the laser pulse; $K_p$ = laser-plasma energy coupling; $\sigma$ = efficiency of conversion to shock wave; $\alpha$ = thermal/kinetic ratio in the shock adiabat, $w_0$ = specific vaporisation heat, $\rho_0$ = solid metal density).

Accurate measurements of craters volumes have been performed using an optical confocal profilometer LEICA DCM 3D which allowed measurements of their surface with an accuracy of ~ 1.7 $\mu$m on the planar dimensions and ~ 45 nm on the depth. Fig. 7 gives an example of the crater reading.
The dependence of the crater volumes on foam thickness is shown in Fig. 7 for various densities of the absorber.

4.2. Study on $p^{+\mathrm{11}}\mathrm{B}$ fusion reactions in nanoseconds laser plasmas

Studies on the neutron-less $p^{+\mathrm{11}}\mathrm{B}$ fusion reactions have found interest in nuclear astrophysics and can be important for energy production. Hydrogen and boron are abundant in nature and the fusion energy is released in the form of kinetic energy of $\alpha$ particles. This makes the reaction a candidate for third generation fusion power plants. The possibility of generating $p^{+\mathrm{11}}\mathrm{B}$ fusions in laser produced plasmas has been demonstrated in experiments with picosecond lasers at intensities of $I \approx 10^{18}$ W/cm$^2$.

Experiments at lower intensities ($I \approx 10^{14}$ W/cm$^2$, 3 ns pulse duration) have been performed with the two-beams ABC laser facility in ENEA Frascati, on Boron-doped polyethylene targets, giving some evidence of the production of $\alpha$ particles. Due to the low number of fusion reactions expected in these conditions it is important that the $\alpha$ particles are detected with minimum incertitude. The most recent experimental activity has been dedicated to further analysis of CR 39 with an increased angular coverage of the measurements. In order to obtain a better discrimination against spurious effects due to other particles, the tracks produced in CR39 by $\alpha$’s with different energies are compared with template images simulated numerically according to the model presented in [9]. The possibility of producing $\alpha$’s by high-energy Boron atoms impinging on the protons inside the CR39 rather than in the plasma has been proven experimentally as not relevant.
4.3. Study of microwave fields

A general study of the electromagnetic fields, which develop during the laser-plasma interaction, has been recently started. This study is based on the measurement of signals detected by antennas placed in different positions with respect to the target, both inside and outside the experimental chamber. General purpose antennas as well as specifically designed antennas have been used, the first results obtained in ABC, will be compared with data collected on experiments performed in other laser laboratories.

Figure 8. Tracks from α particles on CR-39 after irradiation of Polythene doped with Boron, observed (left) and simulated (right, with enlarged scale).

Figure 9. Characteristics and typical signals for the analysis of microwave fields during laser plasma interaction.

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