Laser-plasma acceleration techniques
The FLAME project

The original idea to focus light on matter in order to heat it up and modify its state of aggregation can probably be attributed to Archimedes of Syracuse (287-212 B.C.) with his attempts to burn the Roman ships that were besieging the city. Today, in numerous laboratories around the world, matter is brought to the "extreme" conditions of a **plasma** with temperatures of up to billions of degrees using, just like Archimedes, parabolic mirrors to focus light onto the target, but with two further "improvements".

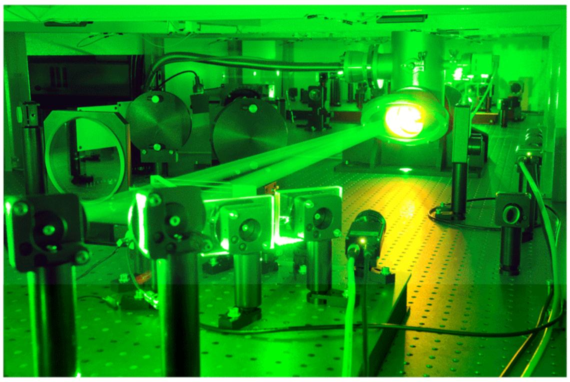
First, the light emitted by a **laser** can be focused onto an area with dimensions close to the wavelength (micrometres) of that light; and second, current technology allows us to concentrate "ordinary" quantities of energy (dozens of Joules) in timescales of the order of femtoseconds (1 fs = 10^{-15} s, or a millionth of a billionth of a second). By combining these numbers it is possible to arrive at an intensity of irradiation of the order of 10^{23} W/cm^2 (as a comparison, the intensity of solar light on the surface of the Earth is just 0.1 W/cm^2).

At these levels of intensity the laser-matter interaction goes beyond the traditional realm of material physics, optics and quantum electronics. For example, for intensities above 10^{16} W/cm^2 the electric field of the electromagnetic wave becomes greater than the field that binds the electron in the hydrogen atom and the laser pulse is able to produce an instantaneous ionisation of the matter which brings it to a plasma state. If the intensity exceeds 10^{18} W/cm^2 the oscillation velocity of the electrons in the electromagnetic field almost reaches the speed of light.

Another quantity that characterises this "super intense" interaction is the **radiation pressure** (the relationship between the intensity and the speed of light), that can reach values of over 10^{16} N/m^2 (hundreds of billions of atmospheres), values that in nature are only reached within stars.

In these regimes the radiation pressure largely dominates the hydrodynamics of the plasma produced, imparting extreme accelerations to the matter, of the order of those reached near **pulsar stars**.

The breadth and the interdisciplinary character of this field of research has produced many experiments all over the world, aiming to develop new infrastructures based on powerful lasers. In Italy, the INFN has started a Strategic Project, called PLASMONX, that has resulted in the creation of a laser (FLAME: Frascati Laser for Acceleration and Multidisciplinary Experiments) capable of producing infrared ($\lambda \approx 0.8$ μm) pulses of about 6 J with a duration of 20 fs and at a frequency of repetition of 10 Hz. FLAME is currently the pulsed laser with the highest average value of power, 60 W.



The photo shows the last stage of the amplification of FLAME. It clearly shows the green light coming from the ten neodymium (Nd-YAG) lasers, duplicated in frequency, directed at a crystal of Titanium-Sapphire, cooled inside a cryostat. The laser radiation emitted by the Titanium-Sapphire, even though it is strongly amplified, is not visible in the photo, because it is emitted near infrared. FLAME, in conjunction with the 200 MeV **LINAC** of the **SPARC** project, will allow unique experiments in which laser pulses and packets of electrons will interact to allow us to study the acceleration of electrons in plasma and the creation of X- and γ- ray sources based on the process of Thomson diffusion.

LASER ACCELERATION OF ELECTRONS IN PLASMAS

The current brake to further development in research in the field of elementary particles, closely connected to the ability to accelerate particles to even higher energies, is the gigantic size of particle accelerators and in their high cost which is difficult to meet even by multinational consortiums such as CERN.

The electric fields inside a plasma can be millions of

conventional accelerators.
For this reason plasmas have long been considered as the ideal situation for accelerating charged particles, reaching energies of thousands of billions of electronVolts (TeV) over distances in the order of just one metre. Creating the most intense electric fields tolerated by a given material of the order of 10^6 V/m, requires about 10^3 km to reach the same energies. Such high electric fields in a plasma can be those associated with an electronic wave of plasma, the longitudinal electric field (i.e. in the direction of the wave's propagation) of which is suitable for accelerating charged particles that move in that direction at a speed close to the **phase velocity** of the wave. The mechanism is analogous to how a surfer acquires kinetic energy (velocity) descending from the crest of the wave that s/he is riding.

The only difference is the nature of the force responsible for the increase in velocity: gravity in the case of the surfer; Coulomb force for an electron in a wave of plasma.

X AND γ SOURCES FROM THOMSON SCATTERING

The Thomson diffusion (scattering) of a laser beam by a packet of ultrarelativistic electrons can be used as the basis for a source of highly monochromatic X/γ radiation and compatible with a wide interval of frequencies. The possibility of having a source of this type presents many advantages in various applications in the field of materials physics and, in particular, in medical diagnostics. The use of monochromatic radiation not only gives a greater resolution in the radiographic image but above all a significant reduction in the dose administered to the patient.
The principal interest in developing this type of source lies in the fact that its dimensions (and consequently its cost) are notably lower than those based on the use of synchrotron radiation.

times more intense than those which can be used in

LASER ACCELERATION OF IONS AND ITS APPLICATION

At the start of this century, three different experimental groups reported the observation that intense jets of protons, with energies of dozens of MeV, were emitted from the back (i.e. from the face opposite the irradiated surface) of thin metallic targets where the protons are present as surface impurities.
Underlying the great interest in sources of energetic protons and ions there is the unique property of these of releasing their energy in the matter principally at the end of their path, which makes the electrons and photons more suitable for applications where a highly localised deposition of energy is required. This is the case in **oncological hadron therapy**, successfully used in hospitals that use "traditional" accelerators as sources of radiation. The prospect of using laser-plasma sources for this purpose is tied to the possibility of reaching the energies necessary (about 200 MeV) and an adequate level of monochromaticity of the spectrum, but above all to be able to obtain these conditions with "compact" laser systems and at a high frequency of repetition. This would allow a significant reduction in the cost in comparison with traditional accelerators.
The innovative techniques of amplification of ultra short laser pulses have started a seemingly unstoppable movement towards increasingly higher intensities. The physical scenarios that are opening up the applications that follow are inspiring numerous research groups across the world. Perhaps the most salient aspect of this field of research is its interdisciplinary nature, bringing together experts in plasma physics, nuclear physics, elementary particle physics and astrophysics as scientists interested in technological applications ranging from the physics of materials to medicine in an "adventure" in which it is still difficult to fully predict its future significance.