# PROPOSAL OF LASER ION BEAM ACCELERATOR FOR INERTIAL FUSION

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*Abstract*

The inertial nuclear fusion with laser beams, relativistic electron beams, ion beams, micro-particle beams and superconducting projectiles has been analytically investigated and numerically calculated by various authors along years and nowadays. Starting from the record laser peak power of 1.25 PW and radiation peak intensity of 100 EW per square centimeter produced at LLNR using the chirped pulse amplification (CPA) laser technology as well as from ELI Nuclear Physics - laser system, 3 APPOLON 10 PW (150 J / 15 fs) (http://www.eli-np.ro/) proposed to be realized, this paper presents the principle and the configuration of a compact ion accelerator operated by an optical laser in an ultra-relativistic regime, for the inertial confinement fusion. Ions acceleration is based on the acceleration mechanism named "Radiation Pressure Acceleration". By the application of this mechanism the calculations for the physical parameters of an ion accelerator operated by laser were made. Calculation results are also presented in this paper.

## INTRODUCTION

Fusion by inertial confinement (ICF) represents an alternative energy source to the nuclear fission energy, hydraulic energy, wind energy, etc. That can be achieved by means of a thermonuclear target (TN) consisting of a capsule housing the fusion fuel located in the centre of a spherical cavity surrounded by a pusher and an ablator.

The fusion fuel may be deuterium (D) and tritium (T) since the nuclear fusion reaction of the two has the most probable efficient section.

The fusion with inertial confinement of D-T is developing on the irradiation of the TN target with particle beams of a certain energy followed by the ablation of the surface material outside the target, the acceleration and compression of the capsule for igniting the fuel core and burning which is spread fast through the compressed fuel.

The fusion of both light nucleus to high temperature and density generates the 17.6 MeV thermonuclear energy by the reaction: D + T → n (14.1 MeV) + α (3.5 MeV). This energy is absorbed by the reactor blanket and converted in thermal energy that is transformed in electric energy by classic methods and techniques.

The TN target containing 1 g D-T produce TN energy of 340 GJ. A fusion reactor with inertial confinement can produce 1.25 GW (electric) with 40 % thermal efficiency with a consumption of 10 mg of DT per second. From the produced electric energy, 1 GW goes to consumer and 36 GW is used for the driver supply.

At present, worldwide, there are more powerful facilities under construction, such as "The National Ignition Facility (NIF) at LLNL [1] and "The Laser Megajoule" (LMJ) in France [2].

There are also programs for light ion accelerators, e.g.: p, $^{12}C$ and heavy ion accelerators e.g.: $^{55}Fe$ → U, as drivers for inertial confinement fusion. This drivers are by types: induction accelerator, linear accelerator, synchrotron [3, 4, 5].

The construction of a 10 PW (150 J / 15 fs) laser system in Bucharest – Magurele led to the elaboration of some programs for the application of the laser beam generated by the laser [6].

One of such applications proposed in the paper, is the use of the laser radioation beam generated by APPOLON 10 PW system to accelerate the ions for to be used as drivers for the conventional ICF or hot-spot ignition with spherical configuration [7].

## LASER ION ACCELERATOR

### *Requirements for ICF*

One of the requirements for ICF is represented by the DT fuel capsule compression. Since the fuel mass depends on fuel density square inverse, one may chose a smaller mass capable to generate a managing energy output. Choose the inertial fusion parameter $\rho R = 2.8$ g/cm$^2$ for the burn-up efficiency $\Phi = \rho R / (\rho R+6\ g/cm^2) = 0.32$, where ρ is the fuel density and R is the target radius [8].

For the fuel mass $M = 10^{-3}$ g, the density of the compressed fuel is $\rho = ((4\pi / 3)(\rho R)^3 / M)^{1/2} = 300$ g/cm$^3$. The required specific energy to compress this mass is given by the Fermi-Dirac internal specific energy $\varepsilon_{FD} = 3 \times 10^5 \rho^{2/3}$ J/g = $1.35 \times 10^7$ J/g. The compression energy for $\alpha_C = 2$ is $E_C = \alpha_{cf}\ \varepsilon_{FD} M = 0.027$ MJ [9].

The energy per gram required to heat a DT plasma at 8.6 keV, which is twice the ideal ignite temperature, is $E_H = 1$ MJ. If 2% of the fuel mass is kept for central hot spot, the energy required to heat this mass would be about 0.02 MJ.

The total energy required for compression and ignition would be about 0.05 MJ. The driver energy required to assemble energy for the plasma efficiency with $\eta_P = 10$ % is equal with 0.5 MJ, resulting in G = 200.

The fusion energy for 1 mg DT with burning efficiency by 32 % is equal with $E_{DT} = \varepsilon_{DT}\Phi M = 3{,}4 \times 10^{11}$ J/g x 0.32 x $10^{-3}$ g = 100 MJ, where $\varepsilon_{DT}$ = 17.6 MeV/5amu is the energy specific to DT fuel per reaction. A nominal 100 MW fusion power plant would consume 1 mg / s of DT.



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### *Driver Requirements*

There are several major reasons to use the ion beams for irradiating the TN targets, directly or indirectly. The first one is the distribution of the absorbed dose deep in the heavy ion beam where towards the end of the range, Gray absorption peak is occurring, like in Figure 1 [10].

One may choose the energy of the heavy ion so that Gray peak should fall on the DT capsule. Also, one may realise the uniform distribution of the absorbed dose on the capsule circumference with the direct and indirect driven alternative.

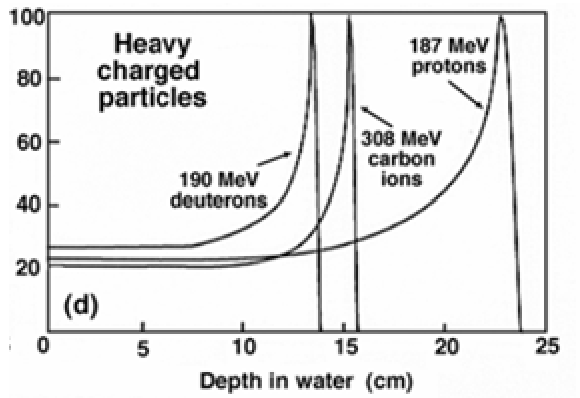


Figure 1: Depth dose in water.

A second reason is that, with the indirect driven alternative the beam has the required intensity for the generation of X-rays in hohlraum. Finally, another reason consists in the high repetition frequency f = 10 Hz, of the driver.

The parameters required for the DT combustible firing and burning are presented in Table 1 [11].

Table 1: Driver requirements

| Parameters | Values |
|---|---|
| Energy beam | 1 – 3 MJ |
| Heavy ion energy | 10 - 20 GeV |
| Peak beam power | 100 - 400 TW |
| Average beam power | 150 MW |
| Deposition characteristics | $10^6$ - $10^8$ J/g |
| Driver Efficiency | 20-30 % |
| Focusing | < 2 mm at 5 to 10m |
| Pulse repetition rate | 1 - 15 Hz |

## PRINCIPLES OF ACCELERATOR OPERATION

Considering that in the end APPOLON shall provide 10 PW output power [12], we have been thinking to use the beam in steps in order to carry-out some experiments related to the heavy ion acceleration for ICF. The idea which is the basis of the heavy ion accelerator with laser consists in the selection of the parameters for the lasers with the power ranging between 1 PW and 10 PW in ultra-relativistic operation regime. The ultra-relativistic regime (URL) is defined for $a_0 = 10^2 \div 10^5$. This regime corresponds to the generation of electric charged particles (electrons, protons, heavy ions, muons, mesons etc) [13].

Ion accelerations to MeV/u level can be made by the “Target Normal Sheath Acceleration” (TNSA) mechanism [14], while for GeV/u level the “Radiation Pressure Acceleration’ (RPA) mechanism can be used, theoretically introduced [15] and firstly experimentally observed to 5 x $10^{19}$ W/cm$^2$ intensity [16, 17].

In this work the RPA acceleration method has been adopted because according to this method, the accelerated ion energy is proportional with laser radiation intensity [18, 19]. TNSA acceleration method allows the ion to acquire energy proportional with the square root of the laser radiation intensity and with a poor efficiency of about 1 % that needs huge lasers. The RPA mechanism has some advantages: ion energy does not depend on its charge, efficiency is up to 10 – 20 % and the neutral beam made-up of ion and electrons is accelerated like an all, the ion bunches has like solid-state densities ($10^{22}$/cm$^3$ - $10^{23}$/cm$^3$) that are about $10^{14}$ times dense than ion bunches from the classic accelerators ($10^8$/cm$^3$) [20-25].

### *Proposal of an Ion Accelerator*

An ion accelerator has, as a main component, the APOLLON laser having intensities about $10^{24}$ W/cm$^2$. The laser beam is optically divided in n under-beams. In this work, take n = 4; 2 of them are in the 1 quadrant (on x and y axis) and the other 2 are in the 3 quadrant (on –x and –y axis).

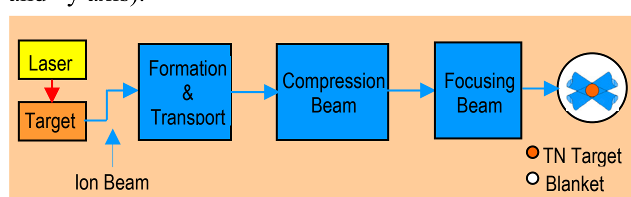


Figure 2: Scheme of an ion accelerator.

The scheme of a beam line with the ion accelerator from four identical lines is shown in Figure 2. The laser beam is focused on a solid metallic target.

At the interaction with this target a ion beam is generated by TNSA or RPA acceleration mechanism which is farther getting into the classic chain of formation and transport, the longitudinal compression of the beam and next, the focusing of the accelerated ion beam on the TN target which is located inside the reaction chamber or the Blanket, in case of Inertial confinement energy production reactor. All these operations are developing outside the reaction chamber. Inside the reaction chamber, there is a device to homogenize the beam at the level of the TN target spherical surface.

The proposed scheme is substituting the standard accelerator (linac, induction linac or synchrotron) with a laser with the power P ranging between 1 PW and 10 PW and an ion solid target.

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The ion accelerator controlled by APPOLON laser with operation in URL regime has the physical parameters calculated by means of the RPA method [18] and are presented in Table 2.

Table 2: Parameters for laser, target and electron beams

| **Laser: circular polarized** | **Values** |
|---|---|
| Pulse energy, W [J] | 195 |
| Peak power, P [PW] | 9,7 |
| Wavelength, λ [μm] | 0.8 |
| Radiation intensity, I [W/cm $^2$] | 1.37x10$^{23}$ |
| Conversion efficiency, χ ξ[%] | 8.65 |
| **$^{192}$Ir Ion beam** | |
| Heavy ion energy, $E_i$ [GeV] | 2 |
| Nucleon energy, $E_u$ [MeV] | 10 |
| Dimensionless pistoning parameter, ξ | 2.2x10$^{-3}$ |
| Total number of ions, N | 5.4x10$^{10}$ |
| **$^{192}$ Ir Target** | |
| Focal spot area, $A_t$ [μm$^2$] | 7.1 |
| Thorium foil thickness, $d_t$ [nm] | 207 |

## CONCLUSIONS

The proposal of a heavy ion accelerator for inertial confinement fusion is based on the characteristics of the ELI Nuclear Physics project which is to be implemented in Magurele-Bucharest. As a result, the accelerator consists of the laser beam and the ion target. The ion acceleration is based on the 'Radiation Pressure Acceleration' mechanism.

It was considered that ions are the proper most particles for the fast ignition of the DT capsule due to Gray peak which occurs at the end of the ion range in the irradiated substance.

The calculation examples given in the text are grounded on the experimental data obtained with the lasers operating in non-relativistic regime and on the numerical simulations around the adimensional amplitude of the lasers $a_0 = 1$, published in specialized magazines.

In order to carry-out a complex project of an accelerator as driver for the inertial confinement fusion it is still necessary to have further data resulted from the studies regarding the heavy particle acceleration in RPA regime, the conversion efficiency, the target geometry and the atomic stopping power of dense ion beams in the substance.

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