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THE BEHAVIOR OF A MAGNETIZED PLASMA UNDER THE ACTION OF LASER WITH HIGH PULSE ENERGY

S.V. Ryzhkov
Bauman Moscow State Technical University, Moscow, Russia
E-mail: ryzhkov@power.bmstu.ru

Simple magnetic traps, such as a cusp and field-reversed configuration are considered for application in high density regime. Magneto-inertial fusion with laser compression of magnetized spherical target and features of laser driven magneto-inertial fusion (LDMIF) are presented. A new fusion scheme which can avoid some of the major difficulties faced in the present approaches in magnetic and inertial confinement fusion is shown. Different schemes of magnetized discharges for LDMIF are discussed. Contributions (fusion power, charged particles and neutrons deposition, thermal conduction, radiation and mechanical work) to a power balance of compressed plasma target are calculated.

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1. INTRODUCTION

There are two basic principles of thermonuclear plasma confinement: magnetic and inertial. In the first case, a dense ($10^{14}...10^{22}$ m^{-3}), high temperature (10...20 keV) plasma is kept in a given volume under the magnetic field pressure, counteracting the plasma pressure. The second approach is based on the use of powerful sources of energy, heating of thermonuclear fuel to high temperatures for a time comparable with the characteristic times of the hydrodynamic expansion of the plasma.

Magneto inertial fusion (MIF) is a relatively new approach [1-3] to producing fusion power that combines features of the more widely studied magnetic (MCF) and inertial confinement fusion (ICF). Like the magnetic approach, the fusion fuel is confined at low density by magnetic fields while it is heated into a plasma, but like the inertial approach, fusion is initiated by rapidly squeezing the target in order to dramatically increase the density of the fuel, and thus its temperature. Although the resulting density is much lower than traditional ICF approaches, it is believed that the combination of longer confinement times and better heat retention will allow the MIF approach to provide the same efficiencies, yet be much easier to build.

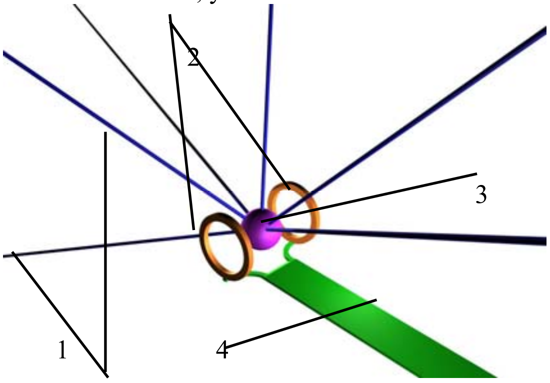


Fig.1. Technical implementation of proposed MIF scheme: 1 – laser beams; 2 - magnetic coils; 3 – target; 4 – discharge system

Typically, in MIF, a magnetized target is compressed by an imploding solid liner [4]. In laser-driven magneto-inertial fusion (LDMIF), a laser beams with high energy pulses (laser intensity $10^{15}...10^{17}$ W/m^2) compresses the target [5]. The motivation for this study is two-fold. First, use this approach to identify possible LDMIF ignition regions. Second, investigate conditions in which the laser driver may contribute significantly to the fusion burn power.

Magnetized cylindrical or spherical targets may be imploded on laser system to compress a magnetic flux to multi-megagauss values [6,7]. The experiments [6,8] demonstrated the bright prospects of laser-driven inertial confinement fusion with magnetized targets.

The principal scheme of magnetic flux compression by laser driver is shown in Fig.1. Like in the experiments [2] the pre-seeded magnetic field can be easily generated by two high-current loops. MIF discharge system is constructed in [2].

Fuel magnetization and preheat significantly lowers the required radial convergence enabling cylindrical implosions to become an attractive path toward generating fusion conditions. Three potential fusion-based technologies for MIF are energy production, space propulsion, and transmutation.

Both MIF and magnetized target fusion (MTF) seeks to develop magnetically confined, inertially controlled thermonuclear fusion system (see Fig.1). The main goal of this paper is modeling of ICF target compression under laser beams to produce ultrahigh magnetic fields. Compressed magnetic field will suppress the thermal transport and lower the ignition requirement.

This research is concerned with the compression of magnetic flux, initially axial in cylindrical geometry by high β plasmas under ICF conditions. The magnetic pressure is a small perturbation to the hydrodynamic pressure in these laser plasmas.

Section 2 discusses the concept of laser-driven magnetic-flux compression. Magnetic confinement systems with high β (the ratio of plasma to external magnetic pressure) for LDMIF are detailed in Sec.3. Analysis of the power balance is presented in Sec.4. A summary is discussed in Sec.5.

Impulse solenoid generates initial magnetic flux in the target (magnetized plasma)
Magnetic field is imbedded in the fuel and laser beams are then accelerated by driver (external source)
Magnetic flux compression increases the pressure inside the target, heating it to ultra-high temperature
Magnetic-flux density is rising, and allows to generate large magnetic field (megagauss range)

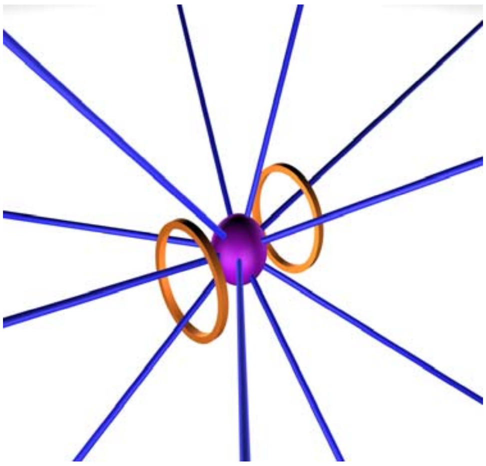


Fig.2. The implosion scheme – the spherical target compression under laser beams

2. LASER DRIVEN MAGNETIC FLUX COMPRESSION

By combination of the benefits of magnetic and inertial confinements, a new fusion scheme is introduced with a dense plasma confined by inertia of laser while its heat is insulated by a self-generated magnetic field. Using the ablative pressure of the laser allows to drive a shell at high implosion velocity, trapping and compressing the external field to magnetize the hotspot center.

Hydrogen may be compressed to more than 10,000 times liquid density by an implosion system energized by a high energy laser. This scheme makes possible efficient thermonuclear burn of small pellets of heavy hydrogen isotopes, and makes feasible fusion power reactors using practical lasers.

A new fusion scheme which can avoid some of the major difficulties faced in the present approaches in magnetic and inertial confinement fusion is described below. Interaction of high energy laser pulses with a magnetized target (Laser Driven Magneto-Inertial Fusion) is shown schematically on Fig.2. Direct compression of magnetized target in MIF may be divided on 4 stages:

1) The system uses a solenoid operated with a pulsed voltage power supply to generate initial (pre-seeded) magnetic field in the imploding target plasma of MIF.

2) The imbedded magnetic field inside the target is compressed along with the target plasma to achieve magnetic insulation. Direct compression of the magnetized plasma (target) by laser driver (laser beams).

3) Thus, magnetic field compression leads to increasing of the plasma pressure (dynamic high-pressure on a target), heating target plasma to ultrahigh temperature.

4) Fuel temperature and pressure both increase to extremely high values with increasing of compression ratio, producing ultra-strong magnetic fields in the megagauss range (> 100 T).

Magnetic field amplification during spherical laser implosion in such scheme may achieve ~ 1000. The amplification of the magnetic field caused by the implosion are compared in [5]. An amplification factor of 140 seen in the high-explosive data [9] represents a convergence initial radius divided by the final radius of 12. Laser-driven implosions have an amplification factor of 560, representing a convergence of 24.

Magnetic-flux compression [10] is a viable path to generating tens of MG magnetic fields with adequate size compression of a metal liner [11] driven by high explosives [9] or by pulsed power. The latter approach has been pursued by the Z-pinch [12] communities. The results from the first experiments on a new approach that provides very effective flux compression are reported here. The field is compressed by the ablative pressure exerted on an imploding ICF capsule by the driving laser [2]. This approach was proposed in the 1980s [13] as a way to achieve record compressed fields with possible applications for fusion [14] but no laser experiments were performed. There are numerous advantages to this approach as the implosion velocity is high (a few 10^5 m/s) and the hot plasma is an effective conductor that traps the pre-seeded magnetic field with minimal resistive diffusion. This approach can be used to magnetize high-energy-density plasmas for a number of applications ranging from controlled fusion to laboratory astrophysics.

3. SPONTANEOUS AND EXTERNAL MAGNETIC FIELDS

Self-generated and externally generated magnetic field imbedded in a plasma are measured in [5,6, 15,16].

The important role played by magnetic fields in laser plasma is by now universally recognized. However, notwithstanding the large number of papers published after first report of registration of the spontaneous magnetic field, no final conclusion can be drawn concerning the mechanisms of this phenomenon. The question of generation of spontaneous magnetic fields in a plasma irradiated be an electromagnetic field was first investigated in [17].

At present, at least five possible mechanisms for the generation of the spontaneous magnetic field can be proposed [18, 19]: 1) the flux of charged particles emitted from the plasma, 2) the charge separation produced when the plasma interacts with the residual gas, 3) the thermoelectric power produced when ∇T is not parallel to ∇n in the plasma, 4) the pressure of the light, and 5) the generation of spontaneous magnetic fields in a plasma acted upon by high-power electromagnetic radiation. This interest is due primarily to the fact that the resultant strong magnetic field can greatly influence the character of the penetration of the light into the plasma and the rate at which transport phenomena take place in the plasma.

The right choice of magnetic configuration is the most important thing for MIF, so you should first consider the various systems based on the principle of magnetic confinement.

Among the various magnetic systems designed for the containment of a high temperature plasma, the most promising are closed systems in which the magnetic field intensity increase towards the periphery. However, in the great majority cases, the equations for the field lines of closed systems are non integrable and an analytical study of the shape of the magnetic field lines, and even more so an analytical study of the motion of the charged particles and of plasma behavior in such fields, does not appear to be a very promising method of investigation. In any case, when studying containment problems, the actual detailed disposition of the magnetic field lines, and the details of the motion of the plasma inside the system, are not especially interesting. It is more important to know whether or not the plasma will remain within the confines of the closed volume.

Antiprobkotron (cusp) [20, 21] and field reversed configuration (FRC) [22] are axis-symmetric magnetic systems (Fig.3). The FRC is alternate system with attractive prospects. Preferable choice of plasma confinement in magnetic device may be combined with properties of inertial confinement.

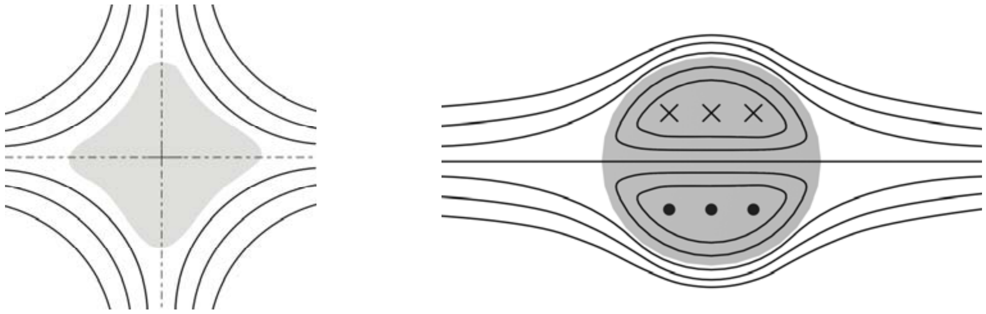
High temperature plasma (target) confined by poloidal magnetic field with taking into account laser system (laser driver) to push and compress plasma of compact toroid (CT).

The interacting physical processes involved introduce disparate time scales. For example, the FRC itself has near-vacuum buffer-field regions that have extremely high Alfven velocity, while the implosion proceeds at a much slower pace. These strongly differing time scales impose stringent accuracy requirements. The kinetic theory of collisionless heating in FRC type of magnetized discharge is developed earlier [23].

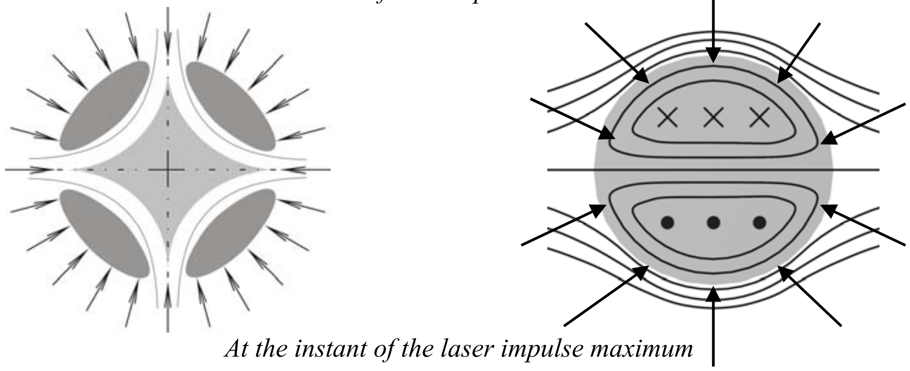
The compact toroid has the unique aspect of self-generated magnetic confinement in a closed configuration, requiring only ancillary fields to provide equilibrium. Two consequences emerge, the high conductivity of a fusion temperature plasma allows for slow decay of the magnetic energy, and the self-contained field configuration allows for CT mobility.

Spherical targets imbedded in a pre-seeded magnetic field are shown in Fig.3. Magnetic field lines shown by continuous lines, laser beams - by arrows.

Proposed cusp magnetic field configuration (antiprobkotron) for laser driven magneto-inertial fusion [24] may be formed on the base of conventional ICF capsule. Although the cusp geometry is not now received much attention in modern magnetic fusion research because of large losses it can be attractive for fusion applications in the limit of high intensity magnetic field that can be generated by laser driven magnetic flux compression.



Before compression



At the instant of the laser impulse maximum

Fig.3. Systems for magnetic flux compression - cusp (antiprobkotron) and FRC (compact toroid)

Oblate (spherical) plasma of FRC is shown on Fig.3. Insight into compact magnetic confinement systems formation, confinement and sustainment should help in the design of future fusion experiments such as the proposed ITER facility. Different applications of compact systems are very attractive [25]. Right now as neutron/proton source, plasma and materials technology, plasma-wall interactions, to test face components.

4. POWER BALANCE OF MAGNETIZED TARGET IN MIF

A power balance in our model includes the power density deposited by the fusion products p_α and p_n, p_m is the contribution due to mechanical work, p_{br} and p_e are, respectively, the power densities lost by radiation (bremsstrahlung is the main mechanism) and by thermal conduction.

The fraction of the α-particle energy deposited inside the considered hot homogeneous sphere of radius R is given by Krokhin and Rozanov [26] as:

$$f_\alpha = \begin{cases} \frac{3}{2}\tau_\alpha - \frac{4}{5}\tau_\alpha^2, \tau_\alpha \le 1/2 \\ 1 - \frac{1}{2\tau_\alpha} + \frac{1}{160\tau_\alpha^3}, \tau_\alpha \ge 1/2 \end{cases},$$

where $\tau_\alpha = R/l_\alpha$ is the ratio of the radius R of the burning sphere to the α-particle free path.

Charged α-particles and neutrons interact with the hot plasma and deposit their energy to the target. The individual fractions f_α and f_n are presented in Fig.4 and 6. Fusion power deposited by α-particles within the hot sphere is shown in Fig.5.

All calculations made for initial density n=10^{21} m^{-3} and magnetic field B = 2 T. The Coulomb logarithm is taken 17. Radius range is chosen for conventional ICF target that may be used for cusp configuration and preformed FRC target.

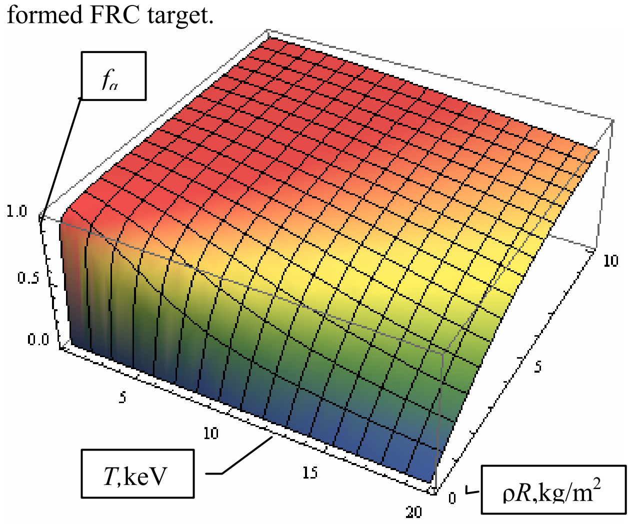


Fig.4. Fraction associated with α-particles versus average plasma temperature T and ρR product

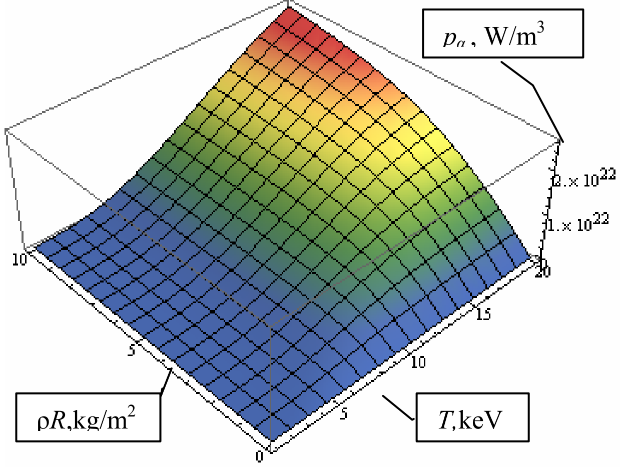


Fig.5. Power density associated with α-particles

Considering volume ignition of a large fuel mass the fractional power deposition for neutrons [27]:

$$f_n = \frac{\rho R}{\rho R + H_n},$$

where ρR is the density-radius product, H_n = 200 kg/m^2 is the constant, which applies to a homogeneous D-T-sphere with uniform neutron source.

The percentage of radiative losses relative to total loss for MIF is two times lower than in MCF system because of lower temperature.

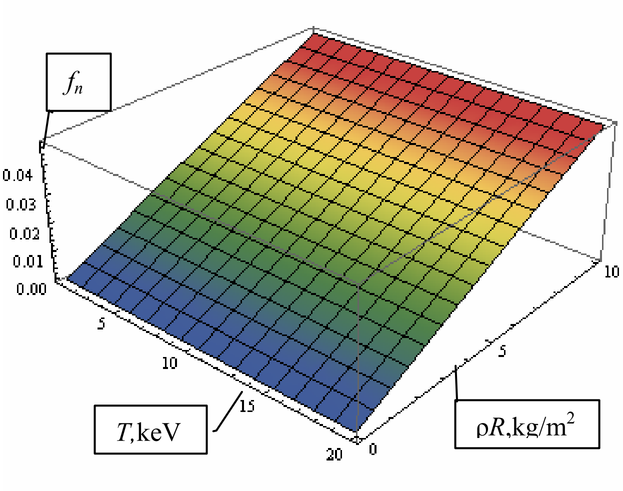


Fig.6. Deposition of neutrons from D-T–reaction to the target compressed by laser beams

PdV work is expansion or compression work due to plasma pressure and a changing volume, but not related to the magnetic field (Fig.7). The expression for mechanical work in our case may be written as

$$W_m = 3\frac{pu}{R} = 3\frac{R_{DT}\rho T u}{R},$$

where u = 10^5 m/s is the velocity of the surface of the sphere (the average velocity of ablation) and R_{DT} = 7.66 x 10^{10} J/(kg keV) is the gas constant for DT-reaction.

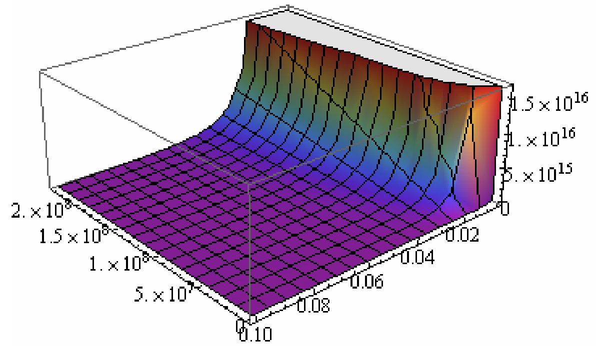


Fig.7. Mechanical (PdV) work u = 1 x 10^5 m/s

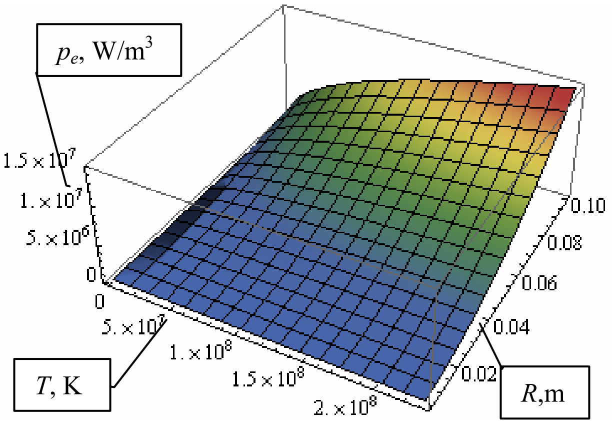


Fig.8. Heat loss due to the electronic thermal conductivity

Thermal conductivity suppression by magnetic field in axial symmetric traps for plasma confinement is shown both experimentally and theoretically. The presence of a magnetic field decreases both longitudinal and transversal heat conduction (Fig.8). Applying an external magnetic field the thermal conductivity decreases by several orders of magnitude. And as a result thermal losses are the lowest part of the energy balance of the target plasma compared with laser fusion, where the heat loss may constitute a substantial portion of total power. The suppressed electronic thermal conductivity corresponds to a 3-7 fold increase in the plasma temperature and density.

CONCLUSIONS

This study points to solution of problem connected with theoretical investigation of methods supplying with magneto inertial fusion (MIF) or magnetized target fusion (MTF) plasma [28].

Magneto-inertial approach to a fusion combines the advantages of magnetic and inertial confinement fusions and provides low-cost simple fusion schemes. Interest in research on MIF has recently been stimulated by: 1) laser-drive magnetic flux compression experiments, 2) the approach to a high β magnetic systems, and 3) advantages in plasma guns and lasers.

Inertially confined plasmas have the attraction that equilibrium, MHD stability, and microinstability problems associated with magnetic confinement can be avoided. The possibility of efficient laser heating of significantly lower plasma densities confined in magnetic configurations appears very remote. The advantage of such a hybrid scheme is that the output of any individual laser may be reduced.

At the density near 10^{23} m^{-3} steady state magnetic confinement at thermonuclear temperatures is possible. Such an approach is to heat a linear high β device. Another possibility is laser heating of magnetically confined plasma.

In this paper spherical configuration of magnetic field for laser driven MIF is proposed. Ultrahigh intensity magnetic filed that can be generated by laser-driven magnetic flux compression of the spherical configuration (e.g. cusp or compact toroid) are made. Power balance of high density and temperature plasma in ultrahigh magnetic fields is analyzed.

Critical to the success of such experiments is to perform full-up multidimensional computational simulations of them [29]. However, there are numerous difficulties in performing those simulations.

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О ПОВЕДЕНИИ ЗАМАГНИЧЕННОЙ ПЛАЗМЫ ПРИ ВОЗДЕЙСТВИИ НА НЕЕ ЛАЗЕРОМ С ВЫСОКОЙ ЭНЕРГИЕЙ ИМПУЛЬСА

С.В. Рыжков

Рассмотрен магнитно-инерциальный термоядерный синтез с лазерным драйвером. Представлено моделирование сильно нелинейного режима взаимодействия мощного лазерного импульса с предварительно замагниченной плазмой. В качестве мишеней выбраны магнитные системы удержания плазмы антипробкотрон (касп) и компактный тор (обращенная магнитная конфигурация). Обсуждаются вопросы самосогласованного и внешнего приложенного магнитного поля. Проведен анализ энергетического баланса *D-T*-плазмы при сферически симметричной имплозии мишени лазером с высокой энергией импульса. Получены основные энергетические характеристики плазменной мишени, вмороженной в магнитное поле.

ПРО ПОВЕДІНКУ ЗАМАГНІЧЕНОЇ ПЛАЗМИ ПРИ ДІЇ НА НЕЇ ЛАЗЕРОМ З ВИСОКОЮ ЕНЕРГІЄЮ ІМПУЛЬСУ

С.В. Рижков

Розглянуто магнітно-інерціальний термоядерний синтез з лазерним драйвером. Представлено моделювання сильно нелінійного режиму взаємодії потужного лазерного імпульсу з попередньо замагніченною плазмою. В якості мішеней вибрано магнітні системи утримання плазми антіпробкотрон (асп) і компактний тор (звернена магнітна конфігурація). Обговорюються питання самоузгодженого і зовнішнього прикладеного магнітного поля. Проведено аналіз енергетичного балансу *D-T*-плазми при сферично симетричній імплозії мішені лазером з високою енергією імпульсу. Отримано основні енергетичні характеристики плазмової мішені, вмороженої в магнітне поле.