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Review

Magneto-Inertial Fusion and Powerful Plasma Installations (A Review)

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Abstract: A review of theoretical and experimental studies in the field of compression and heating of a plasma target in an external magnetic field, which has recently been called magneto-inertial fusion (MIF), has been carried out. MIF is a concept of magnetically driven inertial fusion that involves the magnetization of fuel, laser pre-heating, and magnetic implosion to create fusion conditions. An analysis of the current state of work on the implosion of magnetized targets and the effect of an external magnetic field on the main plasma parameters and system characteristics is presented. Questions regarding the numerical simulation of experiments on the magnetic-inertial confinement of plasma are touched upon. Particular attention is paid to two promising areas of MIF—with plasma jets and with a laser driver (laser beams).

Keywords: magnetized target; magneto-inertial fusion; magnetic field; pinch; nuclear fusion; laser driver; plasma jets

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1. Introduction

Thermonuclear research is currently developing at an impressive rate. A great example of this is the development and construction of the international thermonuclear experimental reactor, ITER. The leader among magnetic traps is a tokamak for plasma confinement. Alternative magnetic configurations are several years behind in terms of the level of research, but their potential capabilities do not exclude future applications. In this regard, issues related to the development of the concept of both a fusion reactor for industrial energy production and fusion installations for the production of medical isotopes, neutron generation, and the creation of rocket engines are becoming relevant.

This review relates specifically to this range of problems and is aimed at justifying the potential application of magneto-inertial fusion (MIF) systems [1–5]; such studies are important, as they expand the range of possible ways to develop future fusion energy.

The main problem of MIF is related to the presence of impurities; however, the use of converging spherical plasma jets to create a plasma liner allows us to solve the problem of the need to destroy the solid liner material after each shot. Therefore, liner systems and a laser driver are of interest.

The research was started and is currently being conducted in Russia, the USA and Japan, but many developments were carried out for the first time in the USSR and the Russian Federation, in particular, the quasi-spherical "double-liner" system was proposed at the I.V. Kurchatov Institute of Atomic Energy (NRC "Kurchatov Institute"), and TRINITI is rightfully considered a pioneer in compact torus research [6]. The main difference between the domestic direction of research is that in the USA and Japan, circuit solutions (conceptual designs) of a thermonuclear reactor have been implemented, whereas in Russia, plasma physical analysis that determines the conditions of ignition of the reaction, and the most basic problem of MIF, is associated with the presence of impurities; however, the use of converging spherical plasma jets to create a plasma liner allows us to solve the problem of the need to destroy the solid liner material after each shot. Therefore, liner systems and a laser driver, while considering both economical and efficient modes, are of interest.

The necessity of the submitted work is related to the following circumstances. Fusion parameters have been obtained on the most famous and advanced tokamak system. A lot has been done on plasma physics, there are many experimental machines, but the project of the international fusion experimental reactor (ITER), which started in 1988, is still far from being completed; the first plasma is planned to be produced in 2026. Compared to the proposed installations at tokamak: (i) a small product of the plasma density by the confinement time; (ii) small beta (the plasma pressure to magnetic field pressure ratio) and energy release; and (iii) impurities.

MIF systems have a small size, but contain high densities. A decrease in thermal conductivity can be achieved by using a seed-magnetic field, which increases with increasing compression. The density of total energy release (power per unit volume) from a fusion reaction~b^2B^4/T. In comparison with a tokamak, pellets, particle injectors for plasma heating, and other additional systems (ICRN, ECRN) are not needed. This greatly simplifies the solution of applied problems for medicine, space exploration, and materials science.

MIF-class installations can operate in different modes and use magnetic configurations with high-pressure compressed plasma, which means it will be possible to create particle sources, and installations for medical use and power reactors.

Different drivers are considered, namely, laser beams and supersonic plasma jets for producing high-density plasma, both quasi-stationary and pulsed installations, in which losses are reduced and dangerous micro-instability does not have time to develop, so the problem of plasma interaction with the wall is not so relevant. In comparison with inertial thermonuclear fusion (ITF or ICF—Inertial Confinement Fusion), the pulse duration and energy confinement time are longer in MIF systems.

Advantages of such systems:

- Spherical compression is an effective way of heating plasma to thermonuclear temperatures (compression ratio is more than 1000).
- Non-stationarity ensures the impossibility of developing plasma instabilities, which leads to a significant reduction in energy losses.
- High degree of burnout of thermonuclear fuel.
- Removal of the problem of plasma interaction with the wall.
- Simpler system design than stationary tokamaks and stellarators.

Magneto-inertial fusion [7–11] is a relatively new approach for energy production, which combines the features and advantages of well-studied magnetic fusion (MCF—Magnetic Confinement Fusion) and inertial fusion.

The relevance and novelty of this task lies in the development of methods for calculating and modeling the compression of a fuel target located in an external magnetic field, and determining promising compression modes and requirements for the technique that provides this compression. The key element in solving this problem is the simulation of particle dynamics, the interaction of fast particles with fuel components in the target and external plasma, neutron fluxes, and the depth of fuel burnout.

Among the different types of plasma confinement and thermonuclear systems, there is no serious research of magneto-inertial fusion (MIF); therefore, numerical analysis and complex calculation are needed to assess the prospects of MIF systems and the implementation of various technologies. An effective means of solving this problem is the use of modern numerical methods for solving complex problems of studying plasma dynamics processes.

One of the urgent tasks of modern physics and controlled thermonuclear fusion is the search for new areas and the analysis of promising alternative (hybrid) systems when creating a reactor and a particle source, as well as obtaining optimal conditions for solving problems related to the use of thermal and neutron fluxes generated in fusion installations with powerful pulsed sources. Advanced technologies based on the use of plasma, in which the synthesis reaction takes place, and magneto-inertial confinement due to super-strong magnetic fields and powerful heating sources, such as lasers and accelerators, are necessary in industries and in the transition to the energy of the future. Systems with high energy density, namely neutron and proton sources, will be in demand in the near future for materials science, analysis and non-destructive testing, production of medical isotopes, destruction of chemical waste, etc.

The prospects for using the magneto-inertial approach, as well as the reasons why the MIF compares favorably with others currently being developed, are mainly in the possibilities of implementing relatively simple methods of confinement and heating the target plasma.

Structurally, the review is compiled as follows. The first chapter presents the basic physical principles and the background of MIF. In the second chapter, MIF schemes with a laser driver are provided, and in the third, variants of MIF with plasma jets are given. The fourth chapter outlines the prospects of MIF installations for using them as neutron generators and other fusion applications. The fifth chapter describes the state of affairs on this topic in the Russian Federation. The sixth chapter contains theoretical studies and possible prototypes, as well as the topic of private companies and fusion startups with magneto-inertial plasma retention. The Appendix A contains the list of MIF devices and companies worldwide.

2. Magneto-Inertial Fusion Concept

Magneto-inertial fusion combines all concepts [12,13], including magnetic compression [14,15] pinches [16–18] and combined systems [19–21]. The specificity of MIF is that this approach requires a shell (liner) [22] to compress and heat a magnetized plasma (target), for example, a compact torus [23]. Under MIF conditions, plasma formation with a high-energy density is possible [24,25].

Various options have been previously considered for an explosive striker, allowing to preserve the magnetic flux: metallic [26], partially evaporating [27], gaseous [28], compressible liquid shells [29], implosion in a hohlraum [30], and the rapid ignition of fusion fuel. Accordingly, theoretical and experimental studies, including the modeling of plasma-shell interaction processes, were carried out for the systems and installations listed above [31–34].

It is necessary to use mathematical modeling, numerical methods and a set of programs to study the interaction processes in the "laser-magnetized target" and "target-internal magnetic shell-plasma liner" systems, and obtain parameters that allow working in those areas and ranges that are unattainable by other installations. The complexity of solving the problem increases significantly in conditions regarding a shortage of experiments on heating, and the compression of plasma by laser beams and high-speed plasma jets in an external field.

MIF schemes represent advanced features for the implementation of new technologies, depending on the tasks set. The paper discusses the prospects of using MIF systems, which have a number of advantages and make it possible to create a reactor and a neutron source using existing experience in fusion research, which also opens the way for new technologies.

For compact magnetic field configurations, there is a simpler design, greater energy release per unit volume and a possibility of using pure (neutron-free) fuel. Both quasi-stationary and pulsed installations for MIF are considered, in which losses are reduced, since dangerous micro instability does not have time to develop; the problem of plasma interaction with the wall is not so relevant. Modeling of fusion combustion is a separate and important problem.

The magneto-inertial approach combines two concepts of controlled thermonuclear fusion (CTF) (as a consequence, simplification of the scheme and reduction of the cost of the system) and can be used to create new plasma retention systems for materials science (neutron source), medicine (proton source) and energy, as well as new effective methods of plasma generation and retention during compression by laser pulses, and plasma jets for the previously, practically, unexplored ranges of magnetic field, density and temperature. Previously (20–30 years ago) there were no such powerful systems, and at present, there are lasers, railguns, current arresters and so on. On the other hand, the cost of calculations required for modeling at a level that allowed the interaction of each jet/beam with the target was prohibitively high.

Such plasma systems can be used for diagnostics and testing of various materials. A feature of the physical formulation of the problem is the presence of a seed magnetic field (superimposed external pulsed field) and compression of the magnetic flux by a laser driver or plasma liner. In this case, beams or jets are introduced from the periphery of the working chamber and compress the magnetized plasmoid that is placed in its center to the state of fusion ignition. The magnetic field "frozen" into the target is compressed together with the plasma, thereby achieving thermal isolation of the plasma from the environment.

Note that the inertial component is responsible for the confinement of particles in MIF, and the energy lifetime determines the magnetic confinement (Table 1). An intense magnetic field suppresses the diffusion in the plasma across the field during the compression phase, and thus, the plasma is heated to fusion temperatures. The large magnetic field created in the target increases the contribution of the reaction products energy to the fusion plasma.

Table 1. The magneto-inertial as fusion concept.

	Particle Retention	Energy Retention	Plasma Density	Time Confinement	Magnetic Field, T	Optical Depth
ICF	Inertial	Inertial	10^5 kg/m^3	τ_E~10 ps	-	R~10
LD *	Inertial		~0.01 g/km^3	τE~100 ns	Initial~1	~0.1 g/cm^2
PL **		Magnetic	~1019 cm^{-3}	τE~100 μσ	Final 1000	~0.01 kg/m^2
MCF	Magnetic	Magnetic	10^{-6} kg/m^3	τ_E~1 s	~10 T	-

* LD—MIF with laser driver, ** PL—MIF with plasma liner, formed by merging high-speed jets.

We emphasize once again that MIF combines all the concepts of the synthesis of the magnetized target (MTF—magnetized target fusion), including magnetic-hydrodynamic compression and the magnetic compression of liners and pinches [35,36]. The MIF concept includes plasma generation and heating schemes; laser heating, Z-pinches, exploding wires, laser–heated plasma inside the solenoid, cryogenic and stabilizing Z-pinches, and other systems [37–41].

3. Laser-Driven Magneto-Inertial Fusion

Laser-driven magneto-inertial fusion (LD MIF) is a wide range of installations, in which, laser systems are used to preheat the target with powerful laser beams and/or compression by lasers with high pulse energy of the target plasma located in a pre-generated (external) magnetic field [42–47].

Among laser installations and the generators based on them, NIF, OMEGA, Gekko, LFEX and others stand out. The new MagNIF pulse system allows the creation of magnetic fields of up to 30 T on the NIF installation [42,43].

Recently, experiments on magneto-inertial fusion have also been conducted at the NIF facility. The complex contains 192 high-power lasers that direct pulses after multistage amplification to a millimeter target with fusion fuel. Tables 2 and 3 with laser parameters are provided below.

The paper [48] assumes the compression of plasma and magnetic flux, due to the quasi-symmetric laser implosion of a magnetized target. A one-dimensional, radiation magnetohydrodynamic code and a formulation of two-fluid equations for modeling a compressible, nonequilibrium, magnetized target plasma have been developed.

The manuscript [49] demonstrates the possibility of generating super-strong magnetic fields that are entirely optical using supercomputer modeling. This article [50] uses the modeling of extended magnetohydrodynamics (MHD).

Table 2. Parameters of NIF with magnetic field.

Parameter	Description
Laser pulse energy	≥1.8 MJ
Laser pulse power	≥500 TW
Laser wavelength	0.35 mcm
Laser pulse duration	up to 20 ns
Laser pulse spot size	≤600 mcm
Magnetic field induction	≤30 T

Table 3. Parameters of OMEGA and OMEGA EP.

Parameter	OMEGA	OMEGA EP
Laser pulse energy	≤30 kJ	≤5 kJ
Laser pulse power	≥27 TW	–
Laser wavelength	351 nm	1.053 mcm
Laser pulse duration	up to 4 ns	up to 100 ps
Laser pulse spot size	≤40 mcm	≤20 mcm
Magnetic field induction	-	≤50 T

The Z-machine at Sandia National Laboratories houses the Magnetized Liner Inertial Fusion (MagLIF) concept (see Table 4), which is already demonstrating fusion temperatures (ion temperature of several keV), significant neutron (10^{11}–10^{13} DD neutrons) production, and the magnetic confinement of charged products [51,52].

Table 4. MagLIF Parameters on Z machine (Pulsed power facility).

Parameter	MagLIF
Current	≤20 MA
Laser pulse energy	≤4 MJ
Laser wavelength	527 nm
Pulse duration	up to 100 ns
Magnetic field	≤20 T

4. Plasma Jet Driven Magneto-Inertial Fusion

There are many devices in the world for implementing magneto-inertial fusion with plasma guns and high-speed plasma jets (PJMIF). Let us focus on the main ones.

In paper [53], desirable magnetized plasma with $\beta > 1$ was defined possibly with strongly entangled open lines of force, which may serve as a suitable target for compression to fusion conditions using a spherical-plasma liner formed by the merging of hypervelocity plasma jets to demonstrate the heating of the target upon compression at a kinetic energy of the plasma liner of $\lesssim$100 kJ (several hundred times below the required energy for a PJMIF reactor).

A brief report [54] contains information on the development of an experiment to form a plasma liner (PLX—Plasma Liner eXperiment). Simulation modeling of a section of a spherically exploding plasma liner formed by the fusion of six hypersonic plasma jets was performed under conditions corresponding to the experiment with the PLX plasma liner [55]. In study [56], a new axial compression experiment with a reversed field configuration (FRC—field reversed configuration) with a high-speed translational θ-pinch plasma in a Keda mirror was conducted.

MagLIF experiments at the Z facility [57] demonstrated the basic principles of magnetic inertial synthesis (MIF) for a wall-bounded plasma. In the article [58], the p- 11B reaction is proposed as a much cleaner alternative for, and ideally, without, a toroidal field. In this work, the dynamics of compression and nuclear burning of p- 11B fuel liners were analyzed and simulated under initial physical conditions. Furthermore, the fusion amplification coefficient, liner parameters, and parameters of the magnetized p- 11B fuel target were compared to those of D-T nuclear fuel.

PJMIF has become a leading concept in MIF, using a coaxial plasma accelerator as an autonomous driver. Such experiment is called PLX [59], for more current experiments and investigations, see Refs. [60–66]. Among the devices located in Russia, the following can be listed: Angara 5-1 (TRINITI) [67,68], the UVL laser (Sarov), and GIT-12 pulse generator (Tomsk). All of these installations use the concept of plasma jets.

Another machine located in RFNC-VNIIEF is the megajoule-level laser system UVL-2M. Its main purpose is to conduct fundamental research in the field of high-density physics and to apply laser-driven inertial confinement in energy production. Currently, the first module of the device has been launched, consisting of eight channels, and is required for conducting inertial confinement fusion experiments and studies of material properties under extreme conditions—at very high temperatures and pressures.

The article [69] describes experiments with a gas-puff Z-pinch surrounded by an external plasma shell, conducted on the generator at currents of 2 MA. Experimental results of neutron and ion measurements on GIT-12 and HAWK were presented in [70].

There are two directions for implementing inertial fusion using Z-pinches. In the first indirect X-ray, irradiation is proposed to compress the target to achieve thermonuclear ignition. The possibilities of using EMGs for ignition, the problems that arise, and ways to solve them are discussed in [71].

Experiments were conducted on the Angara-5-1 installation [72] to study the influence of pulsed ultra-strong currents and soft X-ray radiation (SXR) on plasma formation.

The experiments [73] were conducted to study the self-emission of plasma from heated targets made of layers of different materials (mylar, polypropylene, In, Sn, Au) under the influence of X-ray radiation energy flux (so-called target energy exposure) up to 10 kJ/cm^2.

The article [74] presents an analysis of the dynamic and radiative properties of plasma ablated from a solid target by a laser (1 ns, 10^{12}–10^{13} W/cm^2) as it expands into a homogeneous, strong-magnetic field (up to 30 T) transverse to its main axis of expansion, using experiments and three-dimensional MHD modeling.

For experiments with magnetized laser plasma [75], a pulsed, magnetic field generator with a capacity of up to 15 T was developed, with a volume of several cubic centimeters.

In [76], it is estimated that even with the existing parameters (2 MA) on the MIG (multi-purpose pulse generator), it is possible to achieve thermonuclear fusion provided that a heavy liner rapidly compresses a DT target (~5 ns).

In addition, the data from these studies are of interest for astrophysical applications. For example, work [77] is aimed at experimentally studying the dynamics of laser-induced plasma immersed in a strong-poloidal magnetic field with variable orientation (depending on the expansion of the plasma) and amplitude (up to 30 T).

5. Theoretical Studies and Prototypes

Systems with high-speed plasma jets and powerful laser beams represent the following schemes for MIF: in the first variant, a pre-formed, magnetic configuration is used; and in the second case, an ICF fuel target is used.

The proposed dynamic-plasma compression system combines the technique of generating megagauss magnetic fields (laser driver) with plasma confinement (target) in a magnetic configuration. Therefore, the choice of the magnetic system, i.e., a magnetic trap as a system for magnetically confining plasma for subsequent compression and ignition by laser beams, is crucial.

All systems have a high performance, but FRC and traps have a purely poloidal magnetic field, while the advantage of cusp is its spherical shape and consequently better compression parameters. The implosion scheme is as follows: a spherical target (plasma in a magnetic field of a certain configuration) is compressed under the action of beams. The compressible configuration is maintained by an initial (seeding) magnetic flux, and energy is released in the process. The proposal for creating a combined scheme for magneto-inertial nuclear fusion is formulated in works [78–81].

Numerical modeling of a conducting liner has been well studied for over three decades [82–84], unlike plasma and laser research, which are in the early stages [85,86]. See article [87].

The process of merging magnetized plasma jets with parameters relevant to the plasma jet-driven, magneto-inertial fusion (PJMIF) and the plasma liner experiment (PLX) is simulated in [88].

Article [89] presents the results of a new experimental platform and the report [90] presents measurements from a new platform, in which Z-pinch X-rays from a wire array irradiate a silicon target.

In [91], a supersonic flow of magnetized plasma is created by applying a current pulse with a peak power of 1 MA and a duration of 500 ns to a cylindrical arrangement of parallel wires, known as reverse wiring.

In addition to state corporations, laboratories, and funds, many other different companies from around the world are showing interest in low-radioactive or neutron-free reactions, and alternative thermonuclear fusion systems. Such interest has arisen among companies such as General Fusion, Helion Energy (MSNW), Magneto-Inertial Fusion Technologies Inc. (MIFTI), Sorlox, and Tri Alpha Energy (TAE). These companies are developing energy plants with magneto-inertial confinement plasma with various reactions and power outputs [92].

The Helion plasma accelerator is a prototype of Helion Energy. It is designed to raise nuclear fuel to 100 million degrees and extract electricity directly using a highly efficient pulse approach. According to Faraday's law, the change in the field generates a current that is directly converted into electrical energy, which can be used to power homes and buildings.

TAE Technologies is one of the world's largest private thermonuclear companies. The TAE technology is an advanced FRC configuration. This system is fundamentally different from tokamaks and stellerators. TAE has announced that they plan to have a functional fusion power plant by 2030. To achieve this goal, the TAE team conducts an average of 20 experiments per day on their working reactor, the Norman, which constantly reaches the necessary temperature of 50 million degrees Celsius to sustain the plasma reactor.

HyperJet Fusion Corporation, formerly known as HyperV, is developing a Magneto-Inertial Fusion with Plasma Jets technology. The company is part of a team that includes several leading scientific institutions worldwide, such as the Los Alamos National Laboratory and New Mexico University. Their concept is to create a commercial fusion reactor that operates in a large spherical casing (7.6 m) and uses a large number of plasma jets (around 600). The key difference is the absence of an initial magnetized plasma target. During the ALPHA project, the PLX-α team presented a concept in which a liner with cold D-T fuel and a liner with argon with high Z-pinch were formed. After the high-Z liner fully formed around the D-T liner, pulsed laser waves were fired into the exploding D-T liner to create a magnetic field, allowing the spherical inner liner to function as a target. MIF, with laser jets, has a strong potential due to the relatively high repetition rate of one to two cycles per second, which closely resembles a continuous source of fusion energy.

It is possible to use a thick-liquid inner wall, such as a flowing layer of liquid metal or molten salt, as the main heat carrier to remove heat from the fusion reaction chamber, while reducing damage to the vessel structure from neutrons and serving as a medium for extracting tritium to maintain the D-T fuel cycle in the reactor. The key challenges for developing a commercial reactor are achieving uniform liner pressure, forming a magnetized plasma target, and developing reactor-type plasma guns [93].

ZAP Energy aims to generate fusion energy using Z-pinch stabilized by a sheared flow. One of the latest inventions is the FuZE-Q reactor. This device eliminates the need for the expense and complexity of installing magnetic coils, replacing them with pulses of electrical current along the column of high-conductivity plasma. Because Z-pinch plasma is unstable, it decays within tens of nanoseconds without uniform compression. The new device allows for an increase in the current pulse from 500 kA to 650 kA, which will enable a gain factor of Q = 1 by 2026 [94].

6. Conclusions

Magneto-Inertial Fusion (MIF) is a concept of magnetically driven inertial fusion that involves magnetization of the fuel, laser pre-heating, and magnetic implosion to create fusion conditions. The ability to create controllable electric fields in plasma opens up wide possibilities for plasma technologies [95–105].

Magneto-inertial fusion controlled by a plasma jet involves merging plasma jets with high Mach numbers. MIF devices are of great practical interest to experimenters as they allow for a full range of diagnostics, including temperature and density distributions, instability, and microwave diagnostics. Such devices are more convenient for observing the burning process (with ports on the chamber walls and access to the plasma), as this is impossible with metallic liners.

Further directions of work (mostly for Plasma Jet Driven Magneto-Inertial Fusion):

- the possibility of adding new factors (in addition to compression forces and magnetic field) to increase the efficiency of uniform jet merging and target compression;
- establishing the dependence of the main parameters of plasma jets (density, plasma temperature, velocity, energy content) on pressure, type of working gas, and discharge energy;
- optimization of the design of plasma guns and the power supply system in order to reduce the mass, dimensions and increase the speed of the jets and efficiency.

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Appendix A

Table A1. The List of MIF Devices and Companies.

Angara 5-1	TRINITI, Troitsk, Russia
General Fusion Inc.	Vancouver, BC, Canada
GIT-12	Institute of High Current Electronics, Tomsk, Russia
HAWK	Naval Research Laboratory, Washington, DC, USA
Helion Energy Inc.	Everett, WA, USA
HyperJet Fusion Corporation	Chantilly, VA, USA
LFEX/Gekko	Institute for *Laser* Engineering, Osaka University, Osaka, Japan
MagLIF	Magnetized Liner Inertial Fusion, Sandia National Lab., Albuquerque, NM, USA

Table A1. *Cont.*

MagNIF	Magnetized experiments at the National Ignition Facility
MAGO	magnetic compression, RFNC-VNIIEF, Sarov, Russia
MIFTI (Magneto-Inertial Fusion Technologies Inc.)	Tustin, CA, USA
OMEGA/OMEGA EP	Rochester University, Laboratory For Laser Energetics, Rochester, NY, USA
PLX	Plasma Liner eXperiment, *Los Alamos* National Laboratory, Los Alamos, NM, USA
Sorlox Corporation	Irvine, CA, USA
TAE (Tri Alpha Energy) Technologies	Foothill Ranch, CA, USA
UVL laser	Sarov, Russia
ZAP Energy	Seattle, WA, USA

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