Open Ended Magnetic Systems for Magneto-Inertial Fusion

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## Controlled Fusion Concepts

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Magnetic Fusion (MCF, MFE)</th>
<th>MIF/ MTF (MAGO, MOL)</th>
<th>Inertial Fusion (ICF, LF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat conduction supression</td>
<td>Magnetic</td>
<td>Magnetic</td>
<td>Inertial</td>
</tr>
<tr>
<td>Starting density</td>
<td>$10^{20}$ m$^{-3}$</td>
<td>$10^{23}$ m$^{-3}$</td>
<td>$10^{27}$ m$^{-3}$</td>
</tr>
<tr>
<td>Starting temperature</td>
<td>20 keV</td>
<td>200 eV</td>
<td>cryogenic</td>
</tr>
<tr>
<td>Pulsed</td>
<td>1000 s or longer</td>
<td>A few $\mu$s</td>
<td>A few ns, ps</td>
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<tr>
<td>Driver characteristics</td>
<td>$&gt;150$ MW, 25 MA, (ITER)</td>
<td>10 MJ, 50 MA</td>
<td>1.8 MJ laser (NIF)</td>
</tr>
<tr>
<td>Cost of driver</td>
<td>$10$ billion</td>
<td>$50$ million</td>
<td>$1.2$ billion</td>
</tr>
<tr>
<td>Fusion Yield</td>
<td>0.5-1.5 GW, Z-Pinch Fusion 3 GJ</td>
<td>20 MJ, General Fusion MTF ~600 MJ</td>
<td>5 MJ, NIF 100MJ 1200 MJ/year</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Plasma wall interactions</td>
<td>Wall erosion</td>
<td>Mix of metal and plasma</td>
<td>Rayleigh-Taylor limits convergence</td>
</tr>
<tr>
<td>Plasma Beta</td>
<td>$&lt;1$</td>
<td>$\sim 1$ or $\gg 1$ plasma</td>
<td>Mean age</td>
</tr>
<tr>
<td>“Age”</td>
<td>Pension</td>
<td>Babyhood</td>
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</table>
What is MIF/MTF?

In a magneto inertial fusion (MIF) implosion, an additional thermal insulation of the fuel is provided by a strong magnetic field in an otherwise typical direct-drive ICF target. This differs from magnetized target fusion (MTF), which occupies an intermediate region of parameter space closer to magnetic confinement fusion. Provided that the magnetic field is sufficiently strong, the benefits of this approach are twofold. The plasma can reach ignition temperatures due to the reduced electron thermal conductivity and then, when the nuclear burn develops, the alpha particles will also be confined to the burn region, delivering the energy to support the burn wave.

Involving the application of a magnetic field to inhibit heat flow in an inertially compressed (high pressure) target plasma, and thereby ease the driver requirements. It can take on many possible implementations, both for targets and drivers. At 1 Megabar pressure (or higher), it is in the regime of High Energy Density Physics (HEDP).

MTF is a relatively new approach to producing fusion power that combines features of the more widely studied magnetic (MCF) and inertial (ICF) approaches. 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 MTF approach to provide the same efficiencies, yet be much easier to build.
Introduction to Magneto-Inertial Fusion

**High-gain MIF**
*
*(Laser-Driven Magneto-Inertial Fusion)*

OMEGA EP
Magnetic fields from 1,000 T to 10,000 T are required for typical ICF scenarios

The magnetic field is generated by a large current flowing in small external coils surrounding the target or Laser-driven current drive

Ignition is possible with lower implosion velocity with magnetized targets

NASA 9 ft Diameter Vacuum Chamber

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**Intermediate gain**
*
*(Plasma Jet Driven MIF)*

Shiva Star - FRX-L, CTIX, CT - TOR
Target fusion gain needed for economic power generation can be much lower than for conventional laser driven ICF

Solid and liquid shells (liners)

Non-cryogenic gaseous targets and high-efficiency low cost drivers

RPPL UW IPA, PHD
Magneto-Inertial Approach:
Magnetic insulation (low heat loss) + low implosion velocity (driver energy) + dense plasma

<table>
<thead>
<tr>
<th></th>
<th>Particle confinement</th>
<th>Energy confinement</th>
<th>Plasma density</th>
<th>Confinement time</th>
<th>Density-radius product</th>
<th>Magnetic field</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICF</td>
<td>Inertial</td>
<td>Inertial</td>
<td>$\rho \sim 100$ g/cm³</td>
<td>$\tau_E \sim 10$ ps</td>
<td>$\rho R \sim 10$ kg/m²</td>
<td>---</td>
</tr>
<tr>
<td>LD MIF PJ/ PL</td>
<td>Inertial</td>
<td>Magnetic</td>
<td>$0.1$ g/cm³ $\sim 10^{18}$ cm⁻³</td>
<td>$\tau_E \sim 100$ ns $\tau_E \sim 100$ μs</td>
<td>$\rho R \sim 0.1$ g/cm² $\rho R \sim 0.01$ kg/m²</td>
<td>Init. $\sim 1$ T Fin. $\sim 1000$ T</td>
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<tr>
<td>MCF</td>
<td>Magnetic</td>
<td>Magnetic</td>
<td>$n \sim 10^{21}$ m⁻³</td>
<td>$\tau_E \sim 1$ s</td>
<td>---</td>
<td>$\sim 10$ T</td>
</tr>
</tbody>
</table>

Not just Fusion Energy:
Neutron source, Space Propulsion, radioactive Waste disposal

Planned and proposed:

PLX

NCTX

Internal RMF antennas
Neutral beam port
Internal flux rings

Helion
Where in the universe is MIF?

**Magneto-Inertial Glossary**

MAGO: This acronym has been used exclusively in the U.S. to mean the compression of a magnetized target using chemical explosives, as is done at VNIIEF


MICF/MIIF (a form of MIF/MTF): a spherical ICF hohlraum with a hole in it that allowed electrons to escape and generate a strong B field


MTF: This acronym has a long history, back to the 1960s. It is the generic term used for imploding a magnetized target by a conducting liner. It might also apply to a wall-confined plasma

I.R. Lindemuth, Nuclear Fusion 23 (1983)

MIF (This is a modern acronym by F. Thio): the motivation is to position MTF as the option that lies intermediate between the MFE and IFE communities (not just metal, liquid or heavy ion liners). + Lasers and Plasma Jets

...Driven

**Magneto-Inertial Fusion**

- Impulse solenoid generates initial magnetic flux in the target (magnetized plasma)
- Magnetic field is embedded in the fuel and plasma jets or 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)
MIF/MTF FRC experiments

The MTF approach is currently being studied primarily by the VNIIEF, LANL, AFRL, HyperV, UW and General fusion

Inductive Plasmoid Accelerator (IPA)

G. Votroubek. JFE 27 (2008)

Field Reversed Compression and Heating Experiment, AFRL (2008)

Schematic of the IPA Experiment

Formation       Translation       Compression

FRX-L – Shiva Star


OMEGA EP device – D³He reaction

**MAGO/ MOL in Russia**

**MAGO experiment**

Plasma generator MAGO.  
1, 2 — implosion vessel; 3, 4 — magnetic explosion generators, 5 — detectors, 6 — insulators

**MAGO (Russian abbreviation for MAGnetic Implosion)** in Russia and as MTF (Magnetized Target Fusion) in the United States is an alternative to the main approaches (magnetic confinement systems and inertial confinement fusion).

VNIIIEF (Sarov)

**test bench MOL**

MOL (Russian abbreviation for Magnetic Implosion of Liner)

Uses a magnetic field within a fusion plasma to suppress thermal conduction.

TRINITI (Troitsk) + NIIEFA (S.Petersburg)

1 - magnetic amplifier, 2 - inductive energy storage, 3 - panel, 4 - vacuum system, 5 - plasma current interrupter, 6 - step-up voltage transformer, 7 – magnetic compressor, 8 - capacitor bank, 9 - switching unit for the 2nd step

http://niiefa.spb.ru/res/stc/mit/RUS/Ass/Ass2.htm
Magnetic Configurations for MIF/MTF

Comparison of the main experimental configurations for magnetic-fusion research. The various configurations are shown in a space defined by the level of organization and the strength of the toroidal field.
Targets with solid liners

Diffuse Z-pinch (toroidal field only)

FRC (poloidal field only)

Elongated spheromak (comparable toroidal and poloidal fields)

Initial

Imploded

Initial configuration can be created in situ

FRC has to be created in a separate chamber and injected through a hole in the electrode (not shown)

Spheromak can be created in a “bubble-burst” fashion or in situ
“Cusp-ended theta-pinch” (CETP) was an attempt to mitigate cost of lower $\beta$ regions of end-plugs by length of $\beta = 1$ plasma.

Field-Reversed Configuration (FRC) program and pursued again today.

“Acoustically Driven MTF” M.G. Laberge. ICC (2007)

“The Flying Cusp” an attempt to compress a $\beta = 1$ plasma in an MHD-stable plasma configuration. Note that the liner material, however, is not Rayleigh-Taylor stable to axial deceleration even with rotation.

“MAGO” indicating 3-D, liner compression of wall-supported, magnetized plasma.

Supersonic plasma jets as drivers for MIF

Source for target heating and compression (drivers): Z-pinch, laser radiation, ion beams, plasma guns

Idealized mathematical model

An afterburner layer created by convergence of a second sets of plasma jets

Two possible cases:
- Magnetized
- Un-magnetized

High-Z or plasma liner providing the imploding momentum

The magnetized target

SVR 2010

Plasma Liner Physics Exploratory Experiment (PLX)

Y.C.F. Thio et al. JFE 20 (2001)
Options for plasma jets

2-D Convergence of 64 plasma jets demonstrated at HyperV Plasma Jet accelerator (HyperV Technologies Corp., Virginia Degnan J.H.) - contoured Marshall gun

For spherical 3-D arrays:
- Why not 192 or 300 jets?


Wire-array Z-pinch produces HED plasma jets
(1-MA MAGPIE generator at Imperial College London)


Spherical wire-array Z-pinch
Plasma guns possibilities

Coaxial plasma guns with shaped electrodes

Y.C. Francis Thio, LANL Plasma Jet Workshop. 2008

Advanced PJMIF

Lorentz Force Plasma Accelerator as Standoff Drivers for the plasma liner MTF


The Stanford Cheng Thruster

D.Y. Cheng, Nuclear Fusion 10. 1970
Magneto Inertial Fusion (MIF)/Magnetized Target Fusion (MTF)

**Plasma gun**

**Plasma jet**

**Flow direction**

**Magnetized target plasma**

**The Plasma Liner Physics Exploratory Experiment (PLX)**

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>“Merging Target Jets”</th>
<th>“Stagnation point”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (m)</td>
<td>0.10</td>
<td>0.00537</td>
</tr>
<tr>
<td>n (m⁻³)</td>
<td>10²⁴</td>
<td>6.0</td>
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<tr>
<td>Initial Velocity</td>
<td>27 km/s</td>
<td></td>
</tr>
<tr>
<td>T (keV)</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>B (T)</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Energy req</td>
<td>100 MJ</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*These parameters at instant of impact and at peak compression for DT-liner (Ar, Xe pusher)*

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“Stagnation point”

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>Target</th>
<th>Afterburner</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00537</td>
<td>0.00943</td>
<td></td>
</tr>
</tbody>
</table>

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Credit: John Santarius
Magnetic configurations for MIF
Spherical and Cylindrical Geometry

MIF schemes – configurations GDT, FRC and cusp with plasma and laser driver
We are proposing:

Cusp and mirror trap – for LD MIF

HOSTER - Hybrid Open System Thermonuclear Energetic Reactor

The Plasma Jet Driven MIF power system can be feasibly operated at high yields > 1 GW

PLUR - Plasma Liner Universal Reactor

FRC and GDT – for PLD MIF

PHOT - Plasma Liner Universal Reactor
Our Models of Magnetic Flux Compression

The ICF capsule implosion – Laser beams interaction with the plasma
(Laser-Driven Magneto-Inertial Fusion)
A spherical symmetry model.
A magnetized spherical (cusp) or cylindrical (GDT, mirror trap) target is imploded by high energy laser pulses to compress a pre-seeded magnetic flux to high values.
Target – traditional ICF.
\( \rho_0 \sim 1 \text{ g/sm}^3 (10^{30} \text{ m}^{-3}), r_0 \sim 0.05 \text{ sm}, \Delta r_0 \sim 20 \mu \text{m}, m = 70 \mu \text{g}, B_0 \sim 10 \text{ T}, \tau_E \sim 100 \text{ ns}. \)
Intensity \( \sim 10^{20} \text{ W/m}^2 \)
\( \rho \sim 30 \text{ g/sm}^3, T \sim 7 \text{ keV}, B \sim 3000 \text{ T} \)

The compression of the magnetic trap - Plasma jets interaction with the target
(Plasma Liner Magneto-Inertial Fusion)
Pre-formed magnetized target (e.g. spheromak merging, theta-pinch) compressed by uniformly convergent supersonic plasma jets (plasma liner).
Target initial – \( n \sim 10^{23} \text{ m}^{-3}, r_0 \sim 0.1 \text{ m}, T \sim 10 \text{ eV}, B_0 \sim 1 \text{ T}, m = 0.007 \text{ g} \)
Compression – \( \tau \sim 10 \text{ mks}, \rho R \sim 0.01-0.1 \text{ kg/m}^2, v \sim 10^5 \text{ m/s}, r_0 \sim 0.005 \text{ m}, B \sim 300 \text{ T} \)
Model of a magnetized plasma compressed by high energy laser pulses and plasma jets

The plasma dynamic processes in laser-induced plasma may be described in the framework of system of two-temperature, single-fluid, viscous, radiation plasma dynamics equations in dimensionless form:

\[
\frac{\partial \rho}{\partial t} + \frac{d}{d \xi} \left( \rho \frac{\partial \rho}{\partial \xi} \right) + \frac{d}{dt} \left( \rho \frac{\partial \rho}{\partial \eta} \right) + \frac{1}{J} \left( J \rho \frac{\partial V_x}{\partial \xi} \right) + \frac{1}{J} \left( J \rho \frac{\partial V_y}{\partial \eta} \right) = -\frac{\rho u}{r}
\]

\[
\frac{\partial \rho u}{\partial t} + \frac{d}{d \xi} \left( \rho u \frac{\partial \rho u}{\partial \xi} \right) + \frac{d}{dt} \left( \rho u \frac{\partial \rho u}{\partial \eta} \right) + \frac{1}{J} \left( J \rho u \frac{\partial V_x}{\partial \xi} \right) + \frac{1}{J} \left( J \rho u \frac{\partial V_y}{\partial \eta} \right) = -\frac{\xi}{r} \frac{\partial P}{\partial \xi} - \eta \frac{\partial P}{\partial \eta} - \alpha \frac{\rho u^2}{r} + \frac{S_r}{Re} + \frac{L_e}{c} \left[ \vec{j} \times \vec{B} \right]_r
\]

\[
\frac{\partial \rho v}{\partial t} + \frac{d}{d \xi} \left( \rho v \frac{\partial \rho v}{\partial \xi} \right) + \frac{d}{dt} \left( \rho v \frac{\partial \rho v}{\partial \eta} \right) + \frac{1}{J} \left( J \rho v \frac{\partial V_x}{\partial \xi} \right) + \frac{1}{J} \left( J \rho v \frac{\partial V_y}{\partial \eta} \right) = -\frac{\eta}{r} \frac{\partial P}{\partial \eta} - \xi \frac{\partial P}{\partial \xi} - \alpha \frac{\rho u v}{r} + \frac{S_z}{Re} + \frac{L_e}{c} \left[ \vec{j} \times \vec{B} \right]_z
\]

\[
\frac{\partial \rho e}{\partial t} + \frac{d}{d \xi} \left( \rho e \frac{\partial \rho e}{\partial \xi} \right) + \frac{d}{dt} \left( \rho e \frac{\partial \rho e}{\partial \eta} \right) + \frac{1}{J} \left( J \rho e \frac{\partial V_x}{\partial \xi} \right) + \frac{1}{J} \left( J \rho e \frac{\partial V_y}{\partial \eta} \right) = -\rho \left[ \frac{\partial (J V_x)}{\partial \xi} + \frac{\partial (J V_y)}{\partial \eta} \right] - \alpha \left( \frac{P}{r} - \frac{\rho e u}{r} \right) + \frac{S_e}{Re} \left( \vec{j} \times \vec{E} \right)
\]

Se is the volume power flux due to friction work, thermal conduction processes and energy-release induced by the laser beam interaction with the target plasma, energy released in fusion reaction. The variables Sr, Sz corresponds to the viscous forces in a flux. They represent the sum of works of liquid friction, thermoconductive heat fluxes and plasma heating by laser radiation

\[
S_e = \frac{\left( \mu_{\Sigma}^2 + \mu_{\Sigma} \right)}{2} D + \gamma \Pr \text{div} \left( \sum_k \lambda_{k,\Sigma} \text{grad} T_k \right) + \frac{\text{Re} t_s}{\rho_s e_s} Q_L
\]

A new quasi-monotone numerical method and model for laser-driven magneto-inertial fusion

Distinctive feature of this problem is presence of initial seed fields (the imposed external pulse magnetic field) and compression of a magnetic flux by laser beams (laser driver) and plasma jets (plasma liner).

Obtain the following expression for the source of the magnetic field in a laser plasma (thermo emf):

\[
\frac{\partial \vec{B}}{\partial t} = \text{rot} \left[ \vec{V} \times \vec{B} \right] - \frac{c^2}{4\pi} \frac{t_*}{L^2_*} \text{rot} \left( \frac{\text{rot} \vec{B}}{\sigma} \right) - \frac{t_*}{B_*L_*} \frac{ck}{en_e} \left[ \nabla n_e \times \nabla T \right]
\]

The equation of plasma magnetic field generation is:

\[
\frac{\partial \vec{B}}{\partial t} = \text{rot} \left[ \vec{V} \times \vec{B} \right] - \frac{c^2}{4\pi} \frac{t_*}{L^2_*} \text{rot} \left( \frac{\text{rot} \vec{B}}{\sigma} \right) - \frac{t_*}{B_*L_*} \frac{ck}{en_e} \left[ \nabla n_e \times \nabla T \right]
\]

A dynamic equation for magnetic field may be written in a simplified form:

\[
\frac{\partial B_\phi}{\partial t} = \frac{\partial}{\partial r} \left( uB_\phi \right) + \frac{\partial}{\partial z} \left( vB_\phi \right) + \frac{c^2}{4\pi} \frac{t_*}{L^2_*} \left\{ \frac{\partial}{\partial z} \left( \frac{1}{\sigma_\perp} \frac{\partial B_\phi}{\partial z} \right) + \frac{\partial}{\partial r} \left( \frac{1}{r\sigma_\parallel} \frac{\partial rB_\phi}{\partial r} \right) \right\} - \frac{t_*}{B_*L_*} \frac{ck}{en_e} \left[ \nabla n_e \times \nabla T \right]
\]

In this work the radiation transfer equation is used in the form of multi-group diffusive approach.

\[
\frac{1}{J} \frac{\partial \left( Jq_{i\xi} \right)}{\partial \xi} + \frac{1}{J} \frac{\partial \left( Jq_{i\eta} \right)}{\partial \eta} + \chi_i c U_i = 4\chi_i\sigma_i T^4 \quad \frac{c}{3} \frac{\partial U_i}{\partial \xi} + \chi_i q_{i\xi} = 0 \quad \frac{c}{3} \frac{\partial U_i}{\partial \eta} + \chi_i q_{i\eta} = 0
\]

where \( U(y,z,t) \) is the radiation power density in \( i \)-th spectral group , \( \chi \) is the spectral absorption coefficient.

V.V. Kuzenov, S.V. Ryzhkov. A mathematical model of the interaction of high pulse energy laser with plasma target with initial seed magnetic field // Preprint IPMech # 942 (2010)
The simulations to be relevant to the geometries of cylindrical and spherical targets - Nonstationary Instruments and Codes for fusion Applications (NICA)

An improved two-dimensional radiation-hydrodynamics code which simulates plasmas in cylindrical or spherical geometries is created. It solves single-fluid, two-temperature equations of motion with contributions from diffusion, convection, heat conduction. Electromagnetic processes are described by the Maxwell-Ohm equations in plasma with final conductivity. The transport coefficients in the given system of the equations taking into account magnetized laser plasma. Fusion reactions D-T, D-D (two branches) and D-3He are included in the model. External and spontaneous magnetic fields are taken into account.

\[ v_I = 10^{-7} n_i \left[ \frac{I_H}{I(Z_i)} \right]^{3/2} \exp \left[ - \frac{I(Z_i)}{kT_e} \right] \left[ \frac{I(Z_i)}{kT_e} \right]^{1/2} \left[ 1 + \frac{I(Z_i)}{kT_e} \right]^{-1} \]

\[ v_{F.P} = 6 \times 10^{-14} n_i \left[ \frac{I(Z_i)}{I_H} \right]^{1/2} \left[ \frac{I(Z_i)}{kT_e} \right]^{3/2} \left[ 1 + \frac{I(Z_i)}{kT_e} \right]^{-1} \]

\[ \lambda = 1 \pm 5 \]

\[ v_{T.P} = 3,3 \times 10^{-31} Z_i n_i^2 \left[ \frac{I_H}{I(Z_i)} \right]^{3/2} \left[ \frac{I_H}{kT_e} \right]^{3/2} \left[ 1 + \frac{I(Z_i)}{kT_e} \right]^{-1} \]

The ionization energy of the “average ion” may be approximated by (Z is the nucleus charge):

\[ I(Z_i) = 13,8 \left[ \frac{Z_i^3}{3} + \frac{Z_i^2}{2} + \frac{Z_i}{6} \right] \left( 0,85 + 0,15 Z_i^{2/3} \right) \]

Equations of state for ion and electron component of plasma are following

\[ e_i = \frac{3 kT_i}{2 M_i} \]

\[ P_i = \frac{k \rho T_i}{M_i} \]

\[ \frac{dZ_i}{dt} = Z_i \left( v_I - v_{F.P} - v_{T.P} \right) \]

The electroconductivity (parallel and perpendicular) components are:

\[ \sigma_\parallel = \frac{e^2 n_i \tau_{ei}}{m_e}, \quad \sigma_\perp = \sigma_\parallel \left( 1 + \left( \omega_{pe} \tau_{ei} \right)^2 \right) \]

\[ Y = 1,05 \times 10^{-3} \]

\[ e_e = \frac{3}{2 M_i} \left[ T_e^{3/2} + Z_i \frac{\lambda}{A} \right]^{2/3} \]

\[ P_e = \frac{\rho T_i k}{M_i} \left[ T_e^{3/2} + Z_i \lambda \rho \right]^{2/3} \]

The model is based on splitting method in terms of physical processes and spatial directions, that in spatially smooth solution allows to get seventh order of accuracy. Modified alternatively triangular three-layered iterative scheme is applied for the solution of radiation transport equations, where the time step selected via conjugate directions method. New program takes into account radiation transport in multi-group diffusion approach and gas dynamics according to an improved Lagrangian difference scheme. Mathematical method developed here may be applied for both impact fast ignition and uniform compression calculations.
Absorption coefficients

One can use the mechanism of continuum absorption, the opposite to electron bremsstrahlung process under conditions of local thermodynamic equilibrium (LTE), to define the plasma absorption coefficient for laser radiation:

\[
\chi_v = \frac{4,97 g Z_i n_i n_e}{n^2 \lambda^2 (kT_e)^{3/2}} \frac{1}{\sqrt{1 - n_e/n_c}} \quad \text{cm}^{-1}
\]

- \(\chi_v\) is the laser radiation wavelength (mcm),
- \(n\) are the electron and ion densities correspondingly (cm-3),
- \(kT\) is the electron temperature (keV),
- \(g\) is the Gaunt factor,
- \(n_c = 10^{21} \lambda^{-2}\) is the critical electron density (cm-3).

Non-stationary two dimensional radiation magneto-gas dynamic model is developed by authors. The numerical solution is based on splitting method in terms of physical processes and spatial directions. The calculations of thermodynamic \(e(T, \rho), P(T, \rho)\) and optical \(\chi_i(T, \rho)\) media parameters occur with the aid of computer system ASTEROID, developed by S. Surzhikov.

The averaged Planck and Rosseland mean absorption coefficients:

\[
\chi_i(T, \rho) = \frac{\int_{v_i}^{v_{i+1}} \chi_v(T, \rho) I_{vp} dv}{\int_{v_i}^{v_{i+1}} I_{vp} dv} \quad \chi_i(T, \rho) = \int_{v_i}^{v_{i+1}} \frac{dU_{vp}}{dT} dv / \int_{v_i}^{v_{i+1}} \ell_v dU_{vp} dv
\]

\[
I_{vp} = \frac{2h^3}{c^2} \left( \exp \left[ - \frac{h \nu}{kT} \right] - 1 \right)^{-1} \quad \text{intensity of blackbody radiation,}
\]

\[
\frac{dU_{vp}}{dT} = \frac{15}{4\pi^4} \frac{x^4 \exp(-x)}{(1 - \exp(-x))^2}
\]

Power balance of the target plasma - FRC

\[
\frac{d}{dt}(kT) = \frac{1}{6N} \left\{ \Delta E_\alpha N_r - Q_c - Q_{rad} - pdV - E_B - E_K \right\} \quad N = -N_r = -\frac{N^2}{V} \langle \sigma v \rangle \quad Q_c = 4\pi R^2 g \chi \left( \frac{T - T_b}{R} \right)
\]

\(N\) is the number of deuterons in the target plasma, \(\Delta E_\alpha\) is the amount of energy deposited by an \(\alpha\)-particle in the target,

\(N_r\) is the rate of fusion reactions, \(Q_c\) is the thermal conduction loss rate,

\(E_B\) is the rate of increase of the target magnetic energy, \(E_k\) is the rate of change in the target kinetic energy.

\(g\) is a shape factor for the temperature profile within the target,

\(p_m = pdV = 3\frac{NkTu}{R}\)

\(p_{cond} = \chi T / (S / V)^2 = \chi T / r\)

\(T_b\) is the temperature of the “cold” boundary in contact with the liner (about 100 eV). For a parabolic temperature profile, \(g = 1.25\)

**Braginskii conductivities**

\[\chi = \chi_{\perp e} + \chi_{\perp i}\]

\[\chi_{\perp e} = \frac{n_e k(T_e) \tau_{ee}^{1/2}}{m_e} \left( \frac{4.66\omega_{ce}^2\tau_{ee}^{1/2} + 11.92}{\omega_{ce}^4 + 14.79\omega_{ce}^2\tau_{ee} + 3.77} \right)\]

\[\chi_{\perp i} = \frac{n_i k(T_i) \tau_{ii}^{1/2}}{m_i} \left( \frac{2\omega_{ci}^2\tau_{ii}^{1/2} + 2.64}{\omega_{ci}^4 + 2.7\omega_{ci}^2\tau_{ii} + 0.68} \right)\]

The radiative loss rate

\[Q_{br} = \left\{ \begin{array}{l} 1.706 \cdot 10^{-35} n_e^2 y^{1/2} Z (\log[2y + 0.5] + 0.928) + e^{-2y} + \\ 2.57 \cdot 10^{-35} n_e^2 y^{3/2} (1 + 1.17y + 0.28y^2 - 0.6y^3) \end{array} \right\} \]

Fraction of the \(\alpha\)-particle energy deposited within a target

\[f_\alpha(BR, \rho R) = \left[ \frac{\rho R + \rho C(BR)^2}{\rho R + \rho C(BR)^2 + D} \right] \]

The product BR is evaluated at the plasma boundary in the equatorial plane.

The constant \(C\) depends on the plasma temperature, the field gradient length, and the target radius. The constant \(D\) characterizes the absorption of a \(s\) in a target of a zero magnetic field.

The percentage of radiative losses relative to total loss for MIF is two times lower than in MCF system because of lower temperature.
Plasma Liner Driven Magneto-Inertial Fusion

The thermal conduction from the spherical target

Radiative losses in DT-target

$Q_{br}, \text{W/m}^3$

$Q_{\alpha}, \text{W/m}^3$

$pdV, \text{W}$
Charged $\alpha$-particles deposition to the magnetized DT-target during plasma liner compression

Fraction associated with $\alpha$-particles versus BR-product:
1 - $\rho R = 0.5 \text{ kg/m}^2$; 2 - $\rho R = 0.1 \text{ kg/m}^2$; 3 - $\rho R = 0.01 \text{ kg/m}^2$
$C = 1 \text{ Tm}^{-1}$, $C = 0.117$, $C = 0.01 \text{ Tm}^{-1}$

An approximate dependence on the field gradient of the fraction of the $\alpha$-particle energy deposited within a target:

$$f_\alpha = \frac{\rho(CBR)^2 + R}{\rho(CBR)^2 + R + D}$$

$\rho$ is the plasma mass density, and the product BR is evaluated at the plasma boundary in the equatorial plane. The constant $C$ depends on the plasma temperature, the field gradient length, and the target radius.

Power density associated with $\alpha$-particles

$$p_{\alpha} \approx 5p_\alpha \approx 5/4E_\alpha n^2 <\sigma v>$$
Summary

The possibility of solving the problem of controlled thermonuclear fusion based on magneto inertial approach is proposed. Ultrahigh magnetic field generation in magneto-inertial schemes with LD and PJD MIF is shown.

A magneto-inertial fusion (MIF) approach to inertial confinement fusion (ICF), based on magnetic flux compression is described. This approach benefits from both the high energy density characteristic to ICF and the thermal insulation of the fuel by magnetic fields, typical of MFE.

The general architecture of the MTF fusion reactor based on the localized (evaporating in every shot) spherical blanket, and energy delivered to the target by plasma electrodes (plasma jets) looks quite attractive. Most challenging technology issue is maintaining a low cost of an assembly.

We propose to harness an axisymmetric spherical configuration to create an intense magnetic field by laser beams with high energy/high velocity plasma jets and get quasi-symmetrical compression.

The spherical cusp has advantages (better confinement) compare with other cylindrical open magnetic systems.

A pulsed magneto-inertial fusion scheme with high $\beta$ (the ratio of plasma pressure to the external magnetic field pressure) based on mirror trap, cusp and FRC is considered.

Our concept is a faster and cheaper way (than ITER-NIF, MFE-ICF) to produce fusion (compression the fuel by plasma guns and/or laser beams).
Bremsstrahlung (radiative loss) and Power density associated with $\alpha$–particles

Energy loss due to bremsstrahlung vs. the target plasma radius $R$ and average temperature $T$.

Initial Parameters: $T = 2 \text{ eV}$, $B = 2 T$, $n = 10^{21} \text{ m}^{-3}$. Target: $D$-$T$, $m = 0.007 \text{ g}$, $n_i = 3.2 \times 10^{18} \text{ m}^{-3}$, $T_i = T_e = 2 \text{ eV}$

The power density deposited by the fusion products - alpha-particles $p_{\alpha}$ in DT-target
Mechanical work and Thermal conduction loss rate

$P_{\text{cond}} \text{ W/m}^3$

$R, \text{ m}$

$T, \text{ K}$

Heat loss due to the electronic thermal conductivity

Initial parameters $T = 2 \text{ eV}, B = 2T, n = 10^{21} \text{ m}^{-3}$.

Target: D-T, $n_i = 3.2 \times 10^{18} \text{ m}^{-3}, T_i = T_e = 2 \text{ eV}$

$p_{\text{mech}} \text{ W/m}^3$

$R, \text{ m}$

$T, \text{ K}$

Mechanical (PdV) work for ablation velocity $u = 10^5 \text{ m/s}$ vs. temperature ($1 \text{ eV} = 11600 \text{ K}$) and radius