

## Fusion

**FUNCTION:** Fusion is the process by which two or more atomic nuclei combine to form a single nucleus with a mass less than the sum of the individual masses. This process releases energy, as described by Einstein's famous equation,  $E=mc^2$ . Fusion is a key process in the cores of stars, including our Sun, and is the basis of hydrogen and thermonuclear weapons. The study of fusion is a key area of research in physics, with the goal of developing a clean, sustainable source of energy.

# Fusion

## Physics of a Fundamental Energy Source

### ENERGY SOURCES & CONVERSIONS

(AN OVERVIEW OF ENERGY CONVERSION PROCESSES)

Energy can take on many forms, and various processes convert one form into another. This table shows the primary energy sources and the processes that convert them into useful energy.

Source	Conversion	Useful Energy
Chemical	Burnt fuel $\rightarrow$ Heat	Thermal energy
Geothermal	Heat $\rightarrow$ Steam	Thermal energy
Nuclear	Nuclear fission $\rightarrow$ Heat	Thermal energy
Solar	Photovoltaic cells	Electrical energy

### Physical Parameters of Energy-Releasing Reactions

Reaction Type	Chemical	Fusion	Fission
Sample Reaction	$C + O_2 \rightarrow CO_2$	$D + T \rightarrow He + n$	$U + n \rightarrow Ba + Kr + 3n$
Typical Inputs (to Power Plant)	Coal and Air	$D_2O$ (2% $D_2O$ ) and $T_2O$ (98% $T_2O$ )	Uranium and Lithium
Typical Temp. (K)	1000	10000	100,000,000
Energy Released per kg Fuel (kJ/kg)	$1.5 \times 10^7$	$2.5 \times 10^{11}$	$1.5 \times 10^{14}$

### HOW FUSION REACTIONS WORK

#### NUCLEAR PHYSICS OF FUSION

Fusion of two nuclei releases energy because the mass of the resulting nucleus is less than the sum of the masses of the two original nuclei.

**Binding Energy per Nucleon as a Function of Nucleon Mass**



**Nuclear Reaction Energy:  $E = \Delta E = \Delta(m_1 c^2 + m_2 c^2 - m_3 c^2)$**

For example, if  $E = 10^7$  J, it is energy change per reaction,  $m_1$  is total initial mass,  $m_2$  is total final product mass. The conversion factor is  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ , or  $931.5 \text{ MeV}/c^2$  when  $E$  is in MeV and  $m$  is in atomic mass units, or

Isotope	Species	Mass (u)
$^1H$	Hydrogen	1.007825
$^2H$	Deuterium	2.014102
$^3H$	Tritium	3.016049
$^4He$	Helium	4.002603
$^{12}C$	Carbon	12.000000
$^{16}O$	Oxygen	15.994915
$^{235}U$	Uranium	235.0439299
$^{238}U$	Uranium	238.0507882

**Plasma Reaction Rate Density  $R = n_1 n_2 \langle \sigma v \rangle$**   
 $n_1, n_2$  = Number of reacting species (ions/m<sup>3</sup>),  $\sigma$  = Cross-section (m<sup>2</sup>),  $v$  = Relative velocity (m/s).  
 Note:  $\langle \sigma v \rangle$  is not the fusion power density.

## To make

**fusion:** Fusion is the process by which two or more atomic nuclei combine to form a single nucleus with a mass less than the sum of the individual masses. This process releases energy, as described by Einstein's famous equation,  $E=mc^2$ . Fusion is a key process in the cores of stars, including our Sun, and is the basis of hydrogen and thermonuclear weapons. The study of fusion is a key area of research in physics, with the goal of developing a clean, sustainable source of energy.

### PLASMAS - THE 4<sup>th</sup> STATE OF MATTER

#### CHARACTERISTICS OF TYPICAL PLASMAS

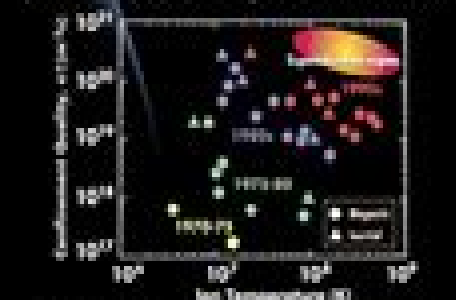
Plasma is a state of matter consisting of a gas of ions and electrons. It is the most common state of matter in the universe, but it is the least understood. Plasma is characterized by its high temperature, low density, and long-range interactions. It is found in stars, interstellar space, and in the Earth's ionosphere.



### ACHIEVING FUSION CONDITIONS

#### EXPERIMENTAL RESULTS IN FUSION RESEARCH

The world's largest fusion experiment, the Joint European Torus (JET), has achieved a record for energy output in a fusion experiment. The experiment achieved a fusion power of 16.1 MW, which is a significant milestone in the development of fusion energy.

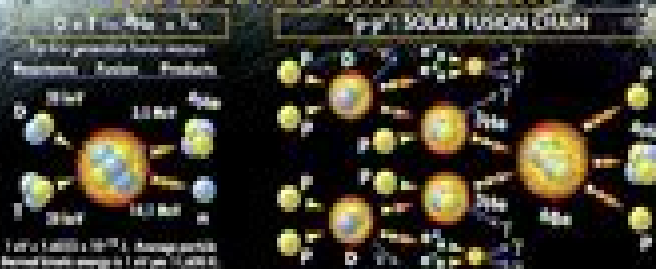


These results are currently limited by the experimental facility, and the next step is to develop a fusion reactor that can sustain a fusion reaction for a long period of time.

### Challenges in Fusion Research: Plasma Instabilities, Confinement, and Heating

There are several challenges in fusion research, including plasma instabilities, confinement, and heating. Plasma instabilities can cause the plasma to lose its confinement, and this is a major problem for fusion research. Confinement is the process of keeping the plasma in a stable state, and this is also a major challenge. Heating is the process of increasing the temperature of the plasma, and this is also a major challenge. These challenges must be overcome in order to develop a fusion reactor.

### TWO IMPORTANT FUSION PROCESSES



### CREATING THE CONDITIONS FOR FUSION

#### PLASMA CONFINEMENT AND HEATING

Confinement	Gravity	Magnetic Fields	Inertial
Plasma requires high temperature, low pressure, and high density to achieve net energy gain.	Gravity is used to confine the plasma in a fusion reactor.	Magnetic fields are used to confine the plasma in a fusion reactor.	Inertial confinement is used to confine the plasma in a fusion reactor.
Typical Issues:	Gravity is not a good confinement method for fusion.	Magnetic fields are not a good confinement method for fusion.	Inertial confinement is not a good confinement method for fusion.
Heating Mechanisms:	Compressor	Compressor	Compressor
	Fusion Product Energy	Fusion Product Energy	Fusion Product Energy

# Fusion Plasma Physics

**Linjin Zheng**



## **Fusion Plasma Physics:**

**Fusion Plasma Physics** Weston M. Stacey, 2005-10-28 Nuclear fusion has the potential to become the most important energy source of the new century But still many problems as e g the confinement of the plasma are not yet solved Thus they are subject to intense research which drives a rapid evolvement of this field of nuclear physics and generates the need for an up to date textbook for graduate students This state of the art textbook assembles the material for a modern course and is aimed at graduate and advanced undergraduate students It both introduces the fundamental principles and theories of fusion plasma physics and presents the most recent topics from various sources in a systematic and concise way Each chapter is rounded off with a set of exercises

**Plasma Physics and Fusion Energy** Jeffrey P. Freidberg, 2008-07-10 There has been an increase in interest worldwide in fusion research over the last decade and a half due to the recognition that a large number of new environmentally attractive sustainable energy sources will be needed to meet ever increasing demand for electrical energy Based on a series of course notes from graduate courses in plasma physics and fusion energy at MIT the text begins with an overview of world energy needs current methods of energy generation and the potential role that fusion may play in the future It covers energy issues such as the production of fusion power power balance the design of a simple fusion reactor and the basic plasma physics issues faced by the developers of fusion power This book is suitable for graduate students and researchers working in applied physics and nuclear engineering A large number of problems accumulated over two decades of teaching are included to aid understanding

**Fusion Plasma Physics** Weston M. Stacey, 2012-10-15 This revised and enlarged second edition of the popular textbook and reference contains comprehensive treatments of both the established foundations of magnetic fusion plasma physics and of the newly developing areas of active research It concludes with a look ahead to fusion power reactors of the future The well established topics of fusion plasma physics basic plasma phenomena Coulomb scattering drifts of charged particles in magnetic and electric fields plasma confinement by magnetic fields kinetic and fluid collective plasma theories plasma equilibria and flux surface geometry plasma waves and instabilities classical and neoclassical transport plasma materials interactions radiation etc are fully developed from first principles through to the computational models employed in modern plasma physics The new and emerging topics of fusion plasma physics research fluctuation driven plasma transport and gyrokinetic gyrofluid computational methodology the physics of the divertor neutral atom recycling and transport impurity ion transport the physics of the plasma edge diffusive and non diffusive transport MARFES ELMs the L H transition thermal radiative instabilities shear suppression of transport velocity spin up etc are comprehensively developed and related to the experimental evidence Operational limits on the performance of future fusion reactors are developed from plasma physics and engineering constraints and conceptual designs of future fusion power reactors are discussed

**Introduction to Plasma Physics and Controlled Fusion** Francis F. Chen, 2013-03-09 TO THE SECOND EDITION In the nine years since this book was first written rapid progress has been

made scientifically in nuclear fusion space physics and nonlinear plasma theory At the same time the energy shortage on the one hand and the exploration of Jupiter and Saturn on the other have increased the national awareness of the important applications of plasma physics to energy production and to the understanding of our space environment In magnetic confinement fusion this period has seen the attainment 13 of a Lawson number  $nTE$  of  $2 \times 10^{21}$  cm<sup>3</sup> sec in the Alcator tokamaks at MIT neutral beam heating of the PL T tokamak at Princeton to  $KT_i$  6.5 keV increase of average to 3% 5% in tokamaks at Oak Ridge and General Atomic and the stabilization of mirror confined plasmas at Livermore together with injection of ion current to near field reversal conditions in the 2XII device Invention of the tandem mirror has given magnetic confinement a new and exciting dimension New ideas have emerged such as the compact torus surface field devices and the E T mirror torus hybrid and some old ideas such as the stellarator and the reversed field pinch have been revived Radiofrequency heating has become a new star with its promise of dc current drive Perhaps most importantly great progress has been made in the understanding of the MHD behavior of toroidal plasmas tearing modes magnetic VII VIII islands and disruptions

*Introduction to Plasma Physics and Controlled Fusion* Francis Chen, 2015-12-17 This complete introduction to plasma physics and controlled fusion by one of the pioneering scientists in this expanding field offers both a simple and intuitive discussion of the basic concepts of this subject and an insight into the challenging problems of current research In a wholly lucid manner the work covers single particle motions fluid equations for plasmas wave motions diffusion and resistivity Landau damping plasma instabilities and nonlinear problems For students this outstanding text offers a painless introduction to this important field for teachers a large collection of problems and for researchers a concise review of the fundamentals as well as original treatments of a number of topics never before explained so clearly This revised edition contains new material on kinetic effects including Bernstein waves and the plasma dispersion function and on nonlinear wave equations and solitons For the third edition updates was made throughout each existing chapter and two new chapters were added Ch 9 on Special Plasmas and Ch 10 on Plasma Applications including Atmospheric Plasmas

Plasma Physics for Controlled Fusion Kenro Miyamoto, 2016-05-12 This new edition presents the essential theoretical and analytical methods needed to understand the recent fusion research of tokamak and alternate approaches The author describes magnetohydrodynamic and kinetic theories of cold and hot plasmas in detail The book covers new important topics for fusion studies such as plasma transport by drift turbulence which depend on the magnetic configuration and zonal flows These are universal phenomena of microturbulence They can modify the onset criterion for turbulent transport instabilities driven by energetic particles as well as alpha particle generation and typical plasma models for computer simulation The fusion research of tokamaks with various new versions of H modes are explained The design concept of ITER the international tokamak experimental reactor is described for inductively driven operations as well as steady state operations using non inductive drives Alternative approaches of reversed field pinch and its relaxation process stellarator including quasi symmetric

system open end system of tandem mirror and inertial confinement are also explained Newly added and updated topics in this second edition include zonal flows various versions of H modes and steady state operations of tokamak the design concept of ITER the relaxation process of RFP quasi symmetric stellarator and tandem mirror The book addresses graduate students and researchers in the field of controlled fusion

*Plasma Physics for Nuclear Fusion* Kenrō Miyamoto, 1989 The original English language edition of this work appeared in 1979 Since then researchers around the world have made slow but steady progress toward the realization of sustained controlled nuclear fusion This new edition has been updated to review the important contributions of the past decade The final chapter Confinement of High Temperature Plasmas has been rewritten entirely to include the recent results of confinement in several types of devices and advances the understanding of wave heating Miyamoto's approach is unique in encompassing Western Soviet and Japanese research in the fusion field The book's 16 chapters are grouped into four major subject areas Chapters in the first part develop the fundamentals of plasma physics and present the conditions of nuclear fusion reactions those in the next two parts provide a magnetohydrodynamic description of plasmas and explain wave phenomena and instabilities by means of a kinetic model Concluding chapters take up the problems of heating diagnostics and confinement Specific topics include the Lawson condition Boltzmann and Vlasov equations plasma equilibrium magnetohydrodynamic instabilities waves in cold and hot plasmas microinstabilities fast neutral beam injection and wave heating and diagnostics using microwaves lasers and energy analyzers Plasma confinement in tokamaks and stellarators multipole fields mirrors and cusps as well as inertial confinement are reviewed Kenro Miyamoto is Professor of Physics at the University of Tokyo

**Magnetically Confined Fusion Plasma Physics** Linjin Zheng, 2019-02-06 This book describes the ideal magnetohydrodynamic theory for magnetically confined fusion plasmas Advanced topics are presented in attempting to fill the gap between the up to date research developments and plasma physics textbooks Nevertheless they are self contained and trackable with the mathematical treatments detailed and underlying physics explained Both analytical theories and numerical schemes are given Besides the current research developments in this field the future prospects are also discussed Nowadays it is believed that if the ideal MHD theory predicts major instabilities none of the magnetic confinements of fusion plasmas can survive The author has also written the book *Advanced Tokamak Stability Theory* In view of its importance the MHD theory is further systematically elaborated in this book The conventional ideal MHD framework is reviewed together with the newly developed multi parallel fluid MHD theory The MHD equilibrium theory and code are described with the non letter X separatrix feature pointed out The continuum modes quasi modes phase mixing and Alfvén resonance heating are analysed The analytical theories for MHD stability in tokamak configurations are systematically presented such as the interchange peeling ballooning toroidal Alfvén modes and kink type of modes The global stability computations are also addressed including resistive wall modes error field amplifications and Alfvén modes etc

*Plasma Physics for Nuclear Fusion* Kenro Miyamoto, 1976      *Nuclear Fusion And*

Plasma Physics - Proceedings Of The International Summer School Y P Huo, Chuan Sheng Liu, Friedrich Wagner, 1995-08-31

The lectures given in the Summer School covered most of the important topics in controlled nuclear fusion and high temperature plasma physics. The topics are as follows: tokamak research, stellarator physics, transport and confinement of high temperature plasma, plasma wall interaction and edge plasma physics, heating and current drive, diagnostics and general plasma theory.

**Fusion Reactor Design** Takashi Okazaki, 2021-11-04. Fusion Reactor Design provides a detailed overview of fusion reactor design, written by an international leader in the field. Nuclear fusion, generating four times as much energy from the same mass of fuel as nuclear fission, is regarded by its proponents as a viable, eco-friendly alternative to gas-fired, coal-fired, and conventional power plants. Although the physics of nuclear fusion is essentially understood, the construction of prototype reactors currently presents significant technical challenges. Fusion Reactor Design: Plasma Physics, Fuel Cycle, System Operation, and Maintenance provides a systematic, reader-friendly introduction to the characteristics, components, and critical systems of fusion reactors. Focusing on the experimental Tokamak reactor, this up-to-date resource covers relevant plasma physics, necessary technology, analysis methods, and the other aspects of fusion reactors. In-depth chapters include derivations of key formulas, figures highlighting physical and structural characteristics of fusion reactors, illustrative numerical calculations, practical design examples, and more. Designed to help researchers and engineers understand and overcome the technological difficulties in making fusion power a reality, this volume provides in-depth knowledge on controlled thermonuclear fusion and its large-scale application in both current fusion reactors and future test reactors. It covers plasma analysis, plasma equilibrium and stability, and plasma transport and confinement, and safety considerations. It explains each component of fusion reactors, including divertors, superconducting coils, plasma heating and current drive systems, and vacuum vessels. It discusses safety aspects of fusion reactors as well as computational approaches to safety aspects of fusion reactors. Fusion Reactor Design: Plasma Physics, Fuel Cycle, System Operation, and Maintenance is required reading for undergraduate and graduate students studying plasma physics and fusion reactor technology and an important reference for nuclear physicists, nuclear reactor manufacturers, and power engineers involved in fusion reactor research and advanced technology development.

**Introduction to Plasma Physics and Controlled Fusion** Francis F. Chen, 1985. **Plasma Physics and Fusion Energy** Jeffrey P. Freidberg, 2007. There has been an increase in interest worldwide in fusion research over the last decade and a half due to the recognition that a large number of new environmentally attractive, sustainable energy sources will be needed to meet ever-increasing demand for electrical energy. Based on a series of course notes from graduate courses in plasma physics and fusion energy at MIT, the text begins with an overview of world energy needs, current methods of energy generation, and the potential role that fusion may play in the future. It covers energy issues such as the production of fusion power, power balance, the design of a simple fusion reactor, and the basic plasma physics issues faced by the developers of fusion power. This book is suitable for graduate students and researchers working in applied physics and

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Abraham Bers, 2016 Plasma is a ubiquitous state of matter at high temperatures The electrodynamics of plasmas encompasses many applications from understanding plasmas in space and the stars to their use in processing semiconductors This textbook at the early graduate level covers basic plasma physics and illustrates its use in many current applications

*Plasma Physics and Controlled Nuclear Fusion* Kenro Miyamoto, 2005-10-20 **Fusion**

Hans Wilhelmsson, 1999-12-01 Journeying through fusion in the universe *Fusion A Voyage Through the Plasma Universe* discusses all aspects of fusion and how they relate to our universe It also studies the attempts to produce fusion energy on Earth The book addresses a wide range of topics from stars galaxies comets pulsars black holes and quasars to the auroras lightning and fluorescent tubes Interestingly the author explores how artists and authors like Vincent van Gogh Leonardo da Vinci and Hannes Alfvén have been fascinated by cosmic phenomena that rely on fusion and plasmas He discusses motions in plasma such as flames waves and whirls similar to those that occur in water The book also examines several other branches of science where parallels can be found with fusion plasmas including ecological systems that provide only very short term weather forecasts and the dramatic changes in the world economy with its explosive tendencies and sometimes catastrophic results It briefly shows how these nonlinear phenomena are at the heart of modern fusion plasma theory

*Magnetic Fusion Energy* George Neilson, 2016-06-02 *Magnetic Fusion Energy From Experiments to Power Plants* is a timely exploration of the field giving readers an understanding of the experiments that brought us to the threshold of the ITER era as well as the physics and technology research needed to take us beyond ITER to commercial fusion power plants With the start of ITER

construction the world's magnetic fusion energy (MFE) enterprise has begun a new era. The ITER scientific and technical basis is the result of research on many fusion plasma physics experiments over a period of decades. Besides ITER, the scope of fusion research must be broadened to create the scientific and technical basis for practical fusion power plants: systems that will continuously convert the energy released from a burning plasma to usable electricity, operating for years with only occasional interruptions for scheduled maintenance. Provides researchers in academia and industry with an authoritative overview of the significant fusion energy experiments. Considers the pathway towards future development of magnetic fusion energy power plants. Contains experts' contributions from editors and others who are well known in the field.

*Introduction to Plasma Physics and Controlled Fusion* Francis F. Chen, 1990

**Nuclear Fusion** Edward Morse, 2018-10-15

The pursuit of nuclear fusion as an energy source requires a broad knowledge of several disciplines. These include plasma physics, atomic physics, electromagnetics, materials science, computational modeling, superconducting magnet technology, accelerators, lasers, and health physics. *Nuclear Fusion* distills and combines these disparate subjects to create a concise and coherent foundation to both fusion science and technology. It examines all aspects of physics and technology underlying the major magnetic and inertial confinement approaches to developing nuclear fusion energy. It further chronicles latest developments in the field and reflects the multifaceted nature of fusion research, preparing advanced undergraduate and graduate students in physics and engineering to launch into successful and diverse fusion-related research. *Nuclear Fusion* reflects Dr. Morse's research in both magnetic and inertial confinement fusion, working with the world's top laboratories, and embodies his extensive thirty-five year career in teaching three courses in fusion plasma physics and fusion technology at University of California Berkeley.



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