

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 original masses. The difference in mass is converted into energy, as described by Einstein's famous equation, $E=mc^2$. This energy is released in the form of heat, light, and other particles. Fusion is the primary energy source of stars, including our Sun, and is the basis of hydrogen bombs. It is also the subject of ongoing research for its potential as a clean, sustainable source of energy for the future.

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 usable energy.

Source	Conversion	Usable Energy
Chemical (Combustion) Nuclear (Fission)	Heat \rightarrow Turbine \rightarrow Electricity Efficiency: 30-40% 1 g fuel \rightarrow 10 kWh	Electricity
Solar	Photovoltaic cells Efficiency: 15-20% 1 m ² \rightarrow 100 kWh	Electricity
Wind	Turbines Efficiency: 40-50% 1 m/s \rightarrow 100 kWh	Electricity
Hydro	Turbines Efficiency: 80-90% 1 m ³ \rightarrow 100 kWh	Electricity

Physical Parameters of Energy-Releasing Reactions

Reaction Type	Chemical	Fusion	Fission
Sample Reaction	$C + O_2 \rightarrow CO_2$ $H_2 + O_2 \rightarrow H_2O$	$D + T \rightarrow He + n$ $4H \rightarrow He + 2H^+$	$^{235}U + n \rightarrow Ba + Kr + 3n$ $^{238}U \rightarrow Th + He$
Typical Inputs (per Power Plant)	Coal and Air	D_2 and T_2	Uranium and Limestone
Typical Temp. (K)	1000	10000	100,000,000
Energy Released per kg Fuel (kJ/kg)	1.5×10^7	2.5×10^8	1.5×10^8

HOW FUSION REACTIONS WORK

NUCLEAR PHYSICS OF FUSION

Fusion of two nuclei releases energy because the final state has a lower mass than the initial state.

Binding Energy per Nucleon as a Function of Mass Number



Nuclear Reaction Energy: $\Delta E = \Delta(m_{\text{reactants}} - m_{\text{products}})c^2$

For example, in the fusion of two deuterium nuclei to form helium-4, the mass difference is approximately 0.025 atomic mass units (amu), which corresponds to an energy release of about 3.5 MeV.

Detailed Nuclear Masses

(The values are in atomic mass units)

Label	Species	Mass (amu)
$m(^1_1H)$	Hydrogen	1.007825
$m(^2_1H)$	Deuterium	2.014102
$m(^3_1H)$	Tritium	3.016049
$m(^4_2He)$	Helium	4.002603
$m(^{235}_{92}U)$	Uranium-235	235.0439299
$m(^{238}_{92}U)$	Uranium-238	238.0507882

Note: 1 amu = 1.660539×10^{-27} kg

Fusion Rate Coefficients



Plasma Fusion Reaction Rate Density: $R = n_1 n_2 \langle \sigma v \rangle$

where n_1, n_2 = Number of reacting species (ions/m³), $\langle \sigma v \rangle$ = Rate coefficient (m³/s), which is a function of temperature and the masses of the reacting species.

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 original masses. The difference in mass is converted into energy, as described by Einstein's famous equation, $E=mc^2$. This energy is released in the form of heat, light, and other particles. Fusion is the primary energy source of stars, including our Sun, and is the basis of hydrogen bombs. It is also the subject of ongoing research for its potential as a clean, sustainable source of energy for the future.

PLASMAS - THE 4th STATE OF MATTER

CHARACTERISTICS OF TYPICAL PLASMAS

Plasma is a state of matter consisting of ionized gases. It is the most common state of matter in the universe, but it is rarely found on Earth. Plasmas are characterized by their high temperature, low density, and collective behavior. They are found in stars, interstellar space, and various laboratory settings.



TWO IMPORTANT FUSION PROCESSES



CREATING THE CONDITIONS FOR FUSION

PLASMA CONFINEMENT AND HEATING

Confinement	Gravity	Magnetic Fields	Inertial
Requires high temperature and high density to maintain the plasma.	Requires high temperature and high density to maintain the plasma.	Requires high temperature and high density to maintain the plasma.	Requires high temperature and high density to maintain the plasma.
Typical Issues:	Typical Issues:	Typical Issues:	Typical Issues:
Heating Mechanisms:	Heating Mechanisms:	Heating Mechanisms:	Heating Mechanisms:

ACHIEVING FUSION CONDITIONS

EXPERIMENTAL RESULTS IN FUSION RESEARCH

Experimental results in fusion research show that achieving the conditions for fusion is a significant challenge. The most common methods for achieving fusion are magnetic confinement and inertial confinement. Both methods require precise control of temperature, density, and confinement time.



Current results are generally limited by the experimental facility and the quality of the plasma. The goal is to achieve a confinement quality of 10 or greater, which would allow for net energy gain from fusion.

Challenges in Achieving Fusion: Plasma Instabilities, Confinement, and Heating

One of the main challenges in achieving fusion is the plasma instabilities. These instabilities can cause the plasma to lose its confinement and cool down, preventing fusion. Another challenge is the heating of the plasma. The plasma must be heated to a temperature of 100 million degrees Celsius to achieve fusion. This is a significant challenge because the plasma is a poor conductor of heat and the heating process is highly inefficient.

Fusion Plasma Physics

Francis F. Chen



Fusion Plasma Physics:

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

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 of a Lawson number nTE of 2×10^{21} cm³ sec in the Alcator tokamaks at MIT neutral beam heating of the PLT tokamak at Princeton to 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

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 **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 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 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 Alexander Piel,2010-06-14 This book is an outgrowth of courses in plasma physics which I have taught at Kiel University for many years During this time I have tried to convince my students that plasmas as different as gas discharges fusion plasmas and space plasmas can be described in a unified way by simple models The challenge in teaching plasma physics is its apparent complexity The wealth of plasma phenomena found in so diverse fields makes it quite different from atomic physics where atomic structure spectral lines and chemical binding can all be derived from a single equation the Schrödinger equation I positively accept the variety of plasmas and refrain from subdividing plasma physics into the traditional but artificially separated fields of hot cold and space plasmas This is why I like to confront my students and the readers of this book with examples from so many fields By this approach I believe they will be able to become discoverers who can see the commonality between a falling apple and planetary motion As an experimentalist I am convinced that plasma physics can be best understood from a bottom up approach with many illustrating examples that give the students confidence in their understanding of plasma processes The theoretical framework of plasma physics can then be introduced in several steps of refinement In the end the student or reader will see that there is something like the Schrödinger equation namely the Vlasov Maxwell model of plasmas from which nearly all phenomena in collisionless plasmas can be derived **Plasma Physics for Nuclear Fusion** Kenro Miyamoto,1976 **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 **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. *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 nuclear engineering. A large number of problems accumulated over two decades of teaching are included to aid understanding. *Comments on Plasma Physics and Controlled Fusion*, 1987. *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. Covers plasma analysis, plasma equilibrium and stability and plasma transport and confinement and safety considerations. Explains each component of fusion reactors including divertors, superconducting coils, plasma heating and current drive systems and vacuum vessels. 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,1990 **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 **Plasma Physics and Fusion Plasma**

Electrodynamics 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 *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 multi faceted 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 **An Indispensable**

Truth Francis Chen,2011-04-11 Recent books have raised the public consciousness about the dangers of global warming and climate change This book is intended to convey the message that there is a solution The solution is the rapid development of hydrogen fusion energy This energy source is inexhaustible and although achieving fusion energy is difficult the progress made in the past two decades has been remarkable The physics issues are now understood well enough that serious engineering can begin The book starts with a summary of climate change and energy sources trying to give a concise clear

impartial picture of the facts separate from conjecture and sensationalism Controlled fusion the difficult problems and ingenious solutions is then explained using many new concepts The bottom line what has yet to be done how long it will take and how much it will cost may surprise you Francis F Chen s career in plasma has extended over five decades His textbook Introduction to Plasma Physics has been used worldwide continuously since 1974 He is the only physicist who has published significantly in both experiment and theory and on both magnetic fusion and laser fusion As an outdoorsman and runner he is deeply concerned about the environment Currently he enjoys bird photography and is a member of the Audubon Society

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