

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 energy production of stars, including our sun, and is the basis of hydrogen bombs. It is also the subject of ongoing research and development, with the goal of creating a sustainable, clean energy source. The process of fusion is complex and requires a deep understanding of nuclear physics and engineering.

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	Burnt Fuel \rightarrow Heat	Thermal Energy
Geothermal	Heat \rightarrow Steam	Thermal Energy
Nuclear	Nuclear Fission \rightarrow Heat	Thermal Energy
Solar	Solar Radiation \rightarrow Heat	Thermal 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)	1.5×10^7	2.5×10^{11}	1.5×10^8

HOW FUSION REACTIONS WORK

NUCLEAR PHYSICS OF FUSION

Fusion reactions release energy by combining light nuclei to form heavier ones.

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, the fusion of two deuterium nuclei ($D + D \rightarrow He + n$) releases energy because the mass of the products is less than the mass of the reactants.

Detailed Nuclear Masses

(The values are in atomic mass units)

Label	Species	Mass (u)
1_1H	Hydrogen	1.007825
2_1H	Deuterium	2.014102
3_1H	Tritium	3.016049
4_2He	Helium	4.002603
n	Neutron	1.008665
p	Proton	1.007276

Note: 1 atomic mass unit (u) is approximately 1.66×10^{-27} kg.

Fusion Rate Coefficients



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

n_1, n_2 = Number of reacting species (ions/m³), $\langle \sigma v \rangle$ = Rate Coefficient (m³/s), σ = Cross-section (m²), v = Relative velocity (m/s).

To make

CHALLENGE: To make fusion reactions occur, the nuclei must be heated to very high temperatures, typically above 100 million Kelvin. At these temperatures, the nuclei are ionized, forming a plasma. The plasma must be held together long enough for the nuclei to fuse. This is a significant challenge because the plasma is extremely hot and tends to expand and cool. Various methods are being developed to confine the plasma, such as magnetic confinement and inertial confinement.

PLASMAS - THE 4th STATE OF MATTER

CHARACTERISTICS OF TYPICAL PLASMAS

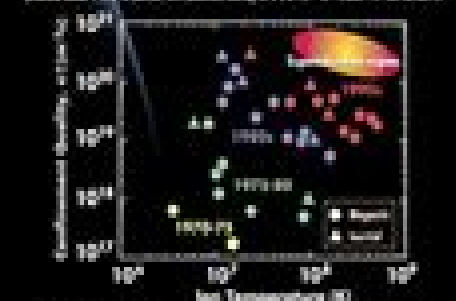
Plasma is a state of matter consisting of ionized gases. It is characterized by high temperatures and the presence of free electrons and ions. Plasmas are found in stars, interstellar space, and in various laboratory settings. They exhibit unique properties, such as collective behavior and the ability to conduct electricity.



ACHIEVING FUSION CONDITIONS

EXPERIMENTAL RESULTS IN FUSION RESEARCH

Experimental results in fusion research show that achieving the conditions for fusion is a significant challenge. Various experiments have been conducted to study the properties of plasmas and to develop methods for confining and heating them. Key results include the demonstration of stable, high-temperature plasmas and the achievement of fusion reactions in laboratory settings.



These results are generally consistent with the theoretical predictions for fusion reactions. The experimental results show that achieving the conditions for fusion is a significant challenge, but it is possible to create and maintain a plasma at high temperatures and densities.

CHALLENGE 1: HOW TO CONFINEMENT PLASMA WITHOUT COLLAPSE OR EXPLOSION

One of the main challenges in fusion research is how to confine the plasma without it collapsing or exploding. The plasma must be held together long enough for the nuclei to fuse, but it must also be able to cool and release energy.

There are two main methods for confining the plasma: magnetic confinement and inertial confinement. Magnetic confinement uses strong magnetic fields to hold the plasma in place, while inertial confinement uses high-pressure lasers to compress the plasma. Both methods have their own challenges, and researchers are working to develop new methods for confining the plasma.

Fusion Plasma Physics

Weston M. Stacey



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 2×10^{21} cm³ 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 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, 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

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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 S T 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 S T 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 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

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