ITER Physics

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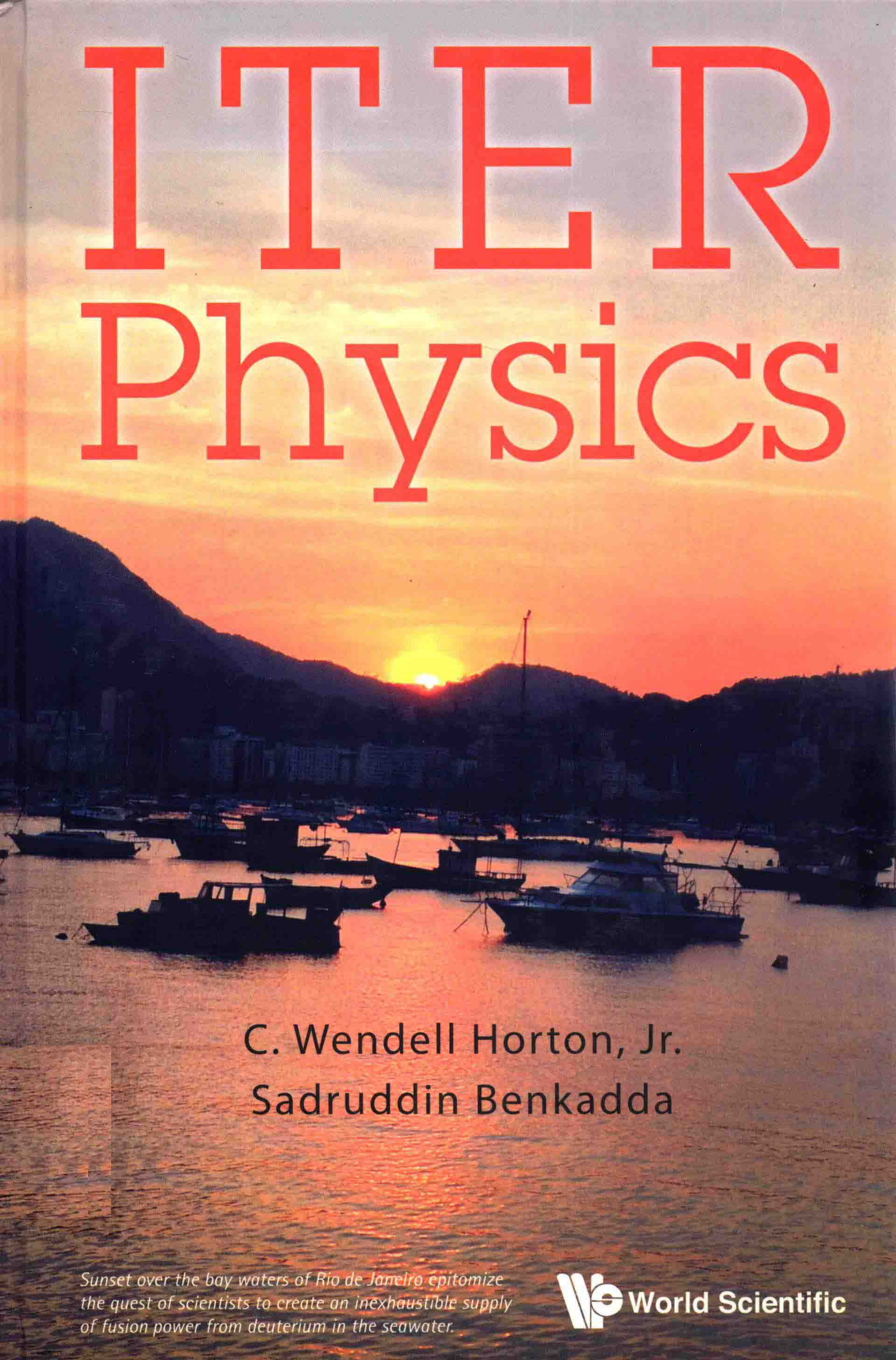

Sunset over the bay waters of Rio de Janeiro epitomize the quest of scientists to create an inexhaustible supply of fusion power from deuterium in the seawater.

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Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

Library of Congress Cataloging-in-Publication Data
Horton, C. W. (Claude Wendell), 1942– author.
ITER physics / C. Wendell Horton, Jr. (University of Texas at Austin, USA), Sadruddin Benkadda (Aix Marseille University, France).
pages cm
Includes bibliographical references and index.
ISBN 978-9814678667 (hard cover : alk. paper)
1. Fusion reactors. 2. Magnetohydrodynamics. 3. Plasma turbulence. I. Benkadda, S., author. II. Title. III. Title: International Thermonuclear Experimental Reactor physics.
TK9204.H65 2015
621.48'40153--dc23

2015005912

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Typeset by Stallion Press
Email: enquiries@stallionpress.com

Printed in Singapore by Mainland Press Pte Ltd.

ITER Physics

Prologue

ITER is a large international *nuclear fusion* science and engineering project under construction in Europe, as the world's largest experimental *tokamak nuclear fusion reactor* (https://www.euro-fusion.org/iter-2/). In Latin language, ITER means "the way," which, as explained in this book, conveys well that the ITER physics and engineering experiments are important to future generations. Originally, the machine name ITER came from the *acronym* for International Thermonuclear Experimental Reactor. The Latin name reminds one that the way the Earth exists is from the power produced in the Sun from a self-sustained nuclear "burning" or nuclear-reacting ball of hydrogen gas compressed by the pull of gravity. While hydrogen is the dominant gas, the solar plasma has a spectrum of minor elements including C, N, O, Ne, Fe and Ni which correspond closely to the impurities studied in tokamaks, as described in Chapter 4.

Helium (He), the major minor constituent of the solar plasma, is the reaction product of the thermonuclear fusion burning of the hydrogen plasma. The spent fuel from fusion is the element Helium discovered in 1868 by French astronomer Pierre Janssen who found a yellow line (487 nm) in the solar spectrum of the chromosphere while observing light during a total solar eclipse. Janssen observed with a spectroscope of his invention for that purpose as recorded in *The Solar Atomic Emissions*. As described here in Chapters 8 and 9, plasma physicists use modern derivatives of these solar techniques to study all types of emissions from laboratory plasmas hotter than the core of the sun. The atomic line emissions are used to measure the transport of the elements, including helium, that enter the plasma from the walls and the thermal insulating coatings applied to the huge confinement walls of the ITER vessel.

Laboratory fusion plasmas also have a dominant minority of the fully stripped ion of helium He atoms called alpha particles born in the core plasma reaction with a high kinetic energy [3.5 MeV] received from the nuclear reaction of deuterium D and tritium nuclei produced by the collision D+T$\rightarrow$ He[3.5 MeV] + n[14.1 MeV]. This 3.5 MeV helium nucleus, or alpha particle, has a large orbit due to the high energy and larger mass. The alpha particle physics of the ITER plasma is a key area of research and described in Chapters 2 and 3. The high energy [14.1 MeV] neutrons penetrate the metal walls and are slowed down and absorbed in a thick blanket of boron and lithium. To create electric power from fusion reactions, the neutron blanket is designed to absorb the kinetic energy of the neutrons, thus creating a huge thermal power generator. The blanket is laced with lithium that undergoes reactions with neutrons that generate the tritium to fuel the fusion reaction. In this way the fusion machine regenerates the fuel needed to maintain the reaction. Deuterium is abundant in water, and the tritium isotopes of hydrogen are produced in the neutron-lithium reaction in the blanket.

The high energy neutron flux from the "burning plasma" is useful for a wide range of applications, including making pharmaceutical radio isotopes for medical diagnostics and for the burning up of waste products from fission reactors, as described in Chapter 10.

The thermal energy will be used to drive a steam turbine generating electricity free of the carbon (oil, gas, and coal) fuels that are currently used in electric power generation stations. The fusion plasma energy source has no carbon in the fuel cycle and thus will be a "GREEN" electric power source. Other "green" power generators are from solar, wind, and tidal power.

The design of the ITER fusion reactor has evolved from more than fifty years of searching for a device to confine the hydrogen plasma at the solar core temperatures required to reproduce the steady nuclear fusion reactions. The principal ideas on how to approach this project evolved from several research teams in the 1950s shortly after the demonstration of explosive nuclear fusion devices. In 1958 an International Conference was organized by the United Nations in Geneva that opened previously classified research projects attempting to create controlled fusion reactions in laboratories in the United States, the Soviet Union and Great Britain. Sharing of the progress and obstacles from these independent attempts lead to rapid future progress and an international involvement for the future experiments in nuclear fusion.

In the 1960s as a result of numerous experiments with various geometries, it was shown that the toroidal magnetic confinement geometry produced the best results. In particular, the experiments in a toroidal chamber with a large plasma current created by using the plasma itself as the secondary winding in an electrical transformer showed the highest temperature and the longest confinement times. The device constructed in the Kurchatov Laboratory in Moscow by a Soviet team showed a clear advantage over the other machines in the 1960s and continues to lead to the best fusion performance today. The toroidal device is known by the Russian acronym for a "toroidal chamber with a current", which is Tokamak. The tokamak became the internationally accepted name for this type of plasma confinement system with many variations explored in the past fifty years. The ITER design includes all the best results from these design variations. An encyclopedic source for physics and engineering in this toroidal system is found in J. A. Wesson, *Tokamaks*, 3rd Ed. (Oxford University Press, 2004) ISBN:0198509227.

France was an early and steadfast builder of tokamaks. First it was at the laboratory at Fontenay-aux-Roses in the suburb of Paris with a tokamak machine called Tokamak Fontenay-aux-Roses (TFR). The TFR machine showed the efficacy of using high energy neutral atomic beam accelerators to heat the plasma ions to temperatures of tens of thousands of degrees centigrade. The TFR experiments were the first to clearly show the anomalous thermal transport of heat (ion temperature 10^4 K equivalent to 1 KeV of kinetic energy) by the turbulent transport of the hydrogen ions, as explained in Chapter 4.

Core plasmas now reach temperatures ten to twenty times higher than those in the first neutral beam heated tokamak plasmas, exceeding the temperature of the core of the Sun. The nuclear fusion of the hydrogen isotopes becomes fast at these high temperatures, yielding the high energy alpha particle and the 14.1 MeV neutron fluxes that could not be explained by the use of the collisional transport of thermal energy that was used in the 1960s and 1970s, as explained in Chapter 4. The Deuterium-Tritium (D-T) (nuclear fusion reaction) experiments on TFTR at the Princeton Plasma Physics Laboratory clearly ruled out the use of collisional transport models. The confinement data is consistent with the plasma temperature gradient-driven turbulent transport.

Increasing the heating power with externally-accelerated beams of neutral deuterium atoms produce the required tens of megawatts of heating power and is the primary tool used to produced the burning plasma in ITER as described in Chapters 5 and 6. With increased heating power the turbulent thermal transport becomes stronger as described in detail in W. Horton, *Turbulent Transport in Magnetized Plasmas* (World Scientific, 2012), ISBN:978-981-4383-53-0.

The level of auxiliary heating power both from neutral beams and from radio frequency (RF) power has increased steadily over the decades since the 1980s. The neutral beam injection (NBI) power P_{nbi} planned for ITER experiment is 33 to 50 MW. Other heating powers from RF antennas on the inside vessel wall are shown in Table 1.1 for the ITER machine. For comparison the values are 20 MW in the largest fusion power tokamak operating today shown for the Joint European Torus called JET and the previous Japanese machine JT-60U described in Chapter 6.

Subsequently, from the mid-1900s onward, many laboratories around the world reproduced outstandingly successful results in the tokamak fusion experiments. Thus, there is an extensive international database for the performance of the tokamak.

Contents

Chapter 1

Machine Architecture and Objectives

1.1 Beginning of the ITER Project

ITER began in 1985 as collaboration between four countries: Russia, the European Union (through the EURATOM organization), the USA, and Japan. Conceptual and engineering design phases were carried out under the auspices of the International Atomic Energy Agency (IAEA). By 2000 a design acceptable to all parties was completed. Subsequently, these four parties were joined by the People's Republic of China and the Republic of South Korea. India became the seventh ITER partner in December 2005. The first Director General was Professor Kaname Ikeda and the second Director General was Professor Osamu Motojima. From 2015, the ITER Director is General Bernard Bigot from Commissariat Energie Atomic in France [http://www.cea.fr].

The first organized design activities (1980-1990) for a tokamak fusion reactor design were known as the INTOR project. Those first design activities also looked toward the second phase of a demonstration machine to follow the ITER proof-of-principle for fusion power. With the ITER project, the design efforts took a new direction. The earlier INTOR design activity is described by W. M. Stacey in *The Quest for a Fusion Energy Reactor*, Oxford, ISBN:978-0-19-973384-2.

In June 2005, the partners officially announced that ITER would be built in the European Union in Southern France. The negotiations that led to this decision ended in a compromise between the EU and Japan, in which Japan was promised directorship of 20% of the research staff at the French location of ITER, as well as having the Director of the administrative body of ITER. In addition, another research facility for the project was built in Japan, and the European Union contributes about 50% of the costs of this new Japanese-based institution located in Amori at the north end of Honshu. In November 2006 an international consortium signed a formal agreement to build the toroidal fusion machine. In September 2007, the People's Republic of China became the seventh country to send their ITER Agreement to the IAEA. By October 2007, the ITER Agreement was established and the ITER Organization legally came into existence as a Treaty between the participating countries.

The initial design in the 1990s from the four partners is shown in Fig. 1.1 as presented by Aymar, *et al.* (1998). This design, called ITER-FDR, was for a major

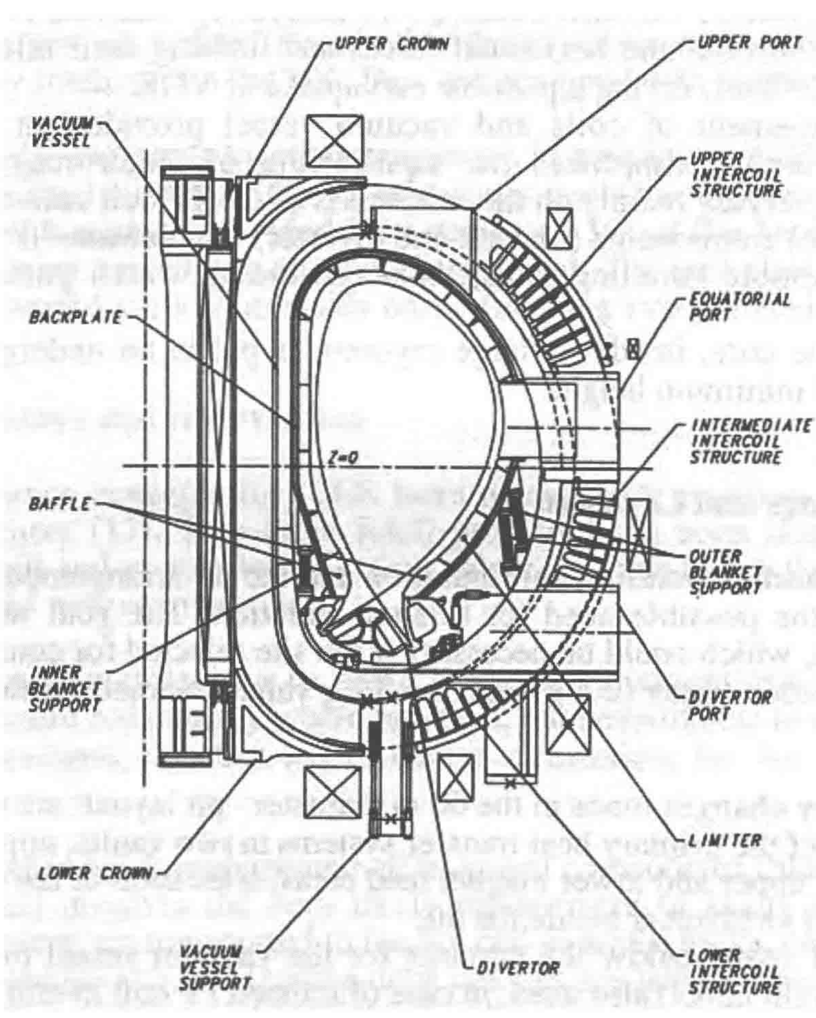

Fig. 1.1 Cross-section of the original 1996 ITER-FDR architecture with $R/a = 8.1\,\mathrm{m}/2.80\,\mathrm{m}$ and $B/I_p = 5.7\,\mathrm{T}/20\,\mathrm{MA}$ designed for fusion power of 1.5 GW. Here FDR refers to the Final Design Report from the Physics Expert Groups published in 1999. The international development path of this design is described in Stacey (2010). Subsequently, the design was charged to that shown in Fig. 1.2 with plasma current reduced to 15 MA in view of lower-transport regimes discovered in the 2000s. Note the X-point of the separatrix line just above the dome of the divertor in the bottom of the inner chamber [Aymar, *et al.* (1998)]. The subsequent progress in improved plasma confinement described in Chapters 4-7 lead to the ITER-FEAT design [Campbell (2001)] with major radius $R = 6.1\,\mathrm{m}$ as shown in Fig. 1.2.

radius of 8 meters with the aim of achieving ignition and running at 1.5 GW of fusion power. By 2000 the perspective had changed, owing to new results described in Chapter 6.

Construction of the ITER complex began in 2007 at a new site next to the Cadarache nuclear laboratory supported by the Commissaries Energie Atomique (CEA). The assembly of the tokamak building and machine was started in 2013-2015. The first components finished were the neutral beam injectors built in Japan.

The construction of the ITER device and the supporting facilities is now (2015) well under way with the latest news available at `https://www.iter.org`.

1.2 Architecture of ITER

The architecture of the ITER fusion reactor is shown in Fig. 1.2. The objectives of the engineering architecture are to design and build within a ten-year period, at reasonable cost, a tokamak capable of producing 500 MW of output fusion power from 50 MW of input power into a mixture of tritium and deuterium plasma. Achieving this power amplification factor $Q_{\mathrm{DT}} = 10$ is considered more assured than the goal of reaching a self-sustained nuclear fusion from ignition, although the machine allows for the possibility of ignition if the thermal energy confinement proves to be sufficient. For a steady-state power system, the power amplification factor is traditionally defined as the Q of the system. ITER construction and research activities are constantly updated on the comprehensive website `https://www.iter.org`.

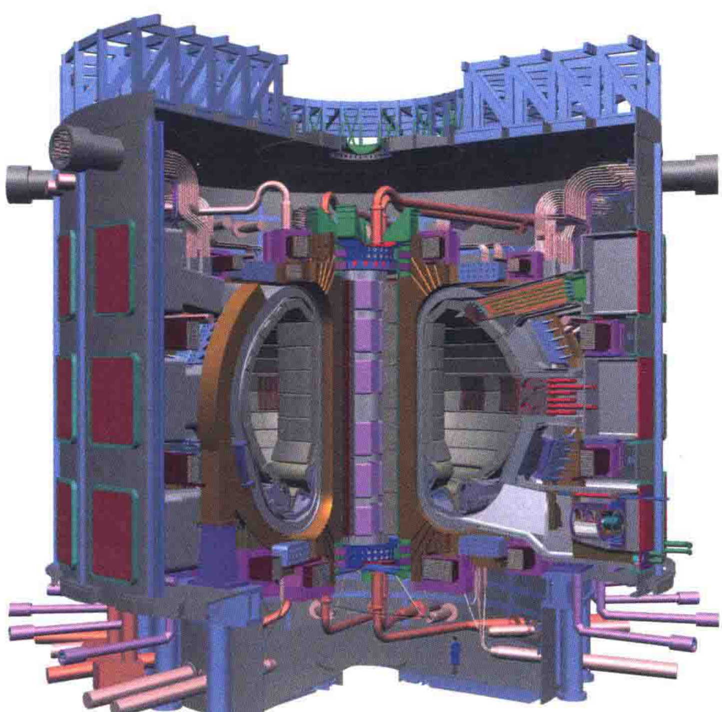

Fig. 1.2 ITER (International Toroidal Experimental Reactor) architecture with $R/a = 6.1\,\mathrm{m}/2\,\mathrm{m}$ with $B_0 = 5.3\,\mathrm{T}$ for confining plasma currents up to $I_p = 15\,\mathrm{MA}$ as given in Table 1.1. The table shows the change from the current European tokamak JET with new ITER fusion experiment.

The reference parameters for ITER, in comparison with the currently-operating Joint European Torus (JET) parameters, are shown in Table 1.1 from Shimada,

Table 1.1 JET and ITER comparison of main parameters from [Shimada, *et al.* (2007)] in *Physics Basis of ITER*. In the left column are the best JET parameters as of 2015 and in the right column are the designed values for ITER.

	Maximum values achieved on JET separately	ITER Design values
R and a	3 m 1.25 m	6.2 m 2 m
Elongation	1.8	1.7
Plasma volume	100 m^3	840 m^3
Magnetic field on axis	4 T	5.3 T
Plasma current in D-shaped plasma	7 MA	16 MA
Plateau current	1 MA for 60 s	15 MA for 500 s
Modes of operation	L, H and ELMy	ELMy
Plasma contact	carbon/beryllium limiters-pumped divertor	beryllium pumped divertor
Neutral injection to the plasma	22 MW	33-50 MW
Coupled ICRH	22 MW	20-40 MW
ECRH	0	20-40 MW
Current drive	3 MA (LH) (5 MA)	15 MA
Solenoid	external	275 V.s
Central density	2×10^{20} m^{-3}	10^{20} m^{-3}
Electron temperature	20 keV	21 keV
Ion temperature	40 keV	18 keV
Q value in DT plasma	0.6 (0.9 net)	10
Fusion power	16 MW	500 MW
Fusion energy	22 MJ in 4 s	120 GJ in 200 s

et al. (2007). The JET deuterium-tritium fusion experiments in the 1997 time frame produced a power amplification factor of $Q \sim 2/3$ for pulse of about one second for 24 MW injected and a power amplification of $Q \sim 1/3$ from a longer four-second pulse driven by 12 MW of auxiliary heating power. Both the short and long pulses produced record amounts of fusion power, or equivalently a record number of neutrons from the DT nuclear fusion reactions. Thus, ITER may still be the first fusion confinement machine to show fusion power amplification factors greater than unity [$Q > 1$] for significant periods of time, meaning for time intervals of order tens of seconds. Reaching such net power amplification for a period time of order 50 to 100 energy confinement times is the key objective of ITER. Following this success a larger machine designed on what is learned from ITER will be used to develop the electric power producing fusion reactor called DEMO.

The ITER machine is designed to produce a long DT fusion power pulse of up to 300 s with a $Q = 10$. The initial ITER design was given to the international fusion community [Aymar, *et al.* (1998)]. The machine architecture and the tokamak building and pit presented by Aymar and his design team are shown in Figs. 1.1. Note the components labeled divertor, divertor port, limiter, vacuum vessel, and blanket. These components are common to all fusion reactors. Following the improved confinement results obtained with internal transport barriers in the Japanese tokamak JT-60U reported by Fujita, *et al.* (1998, 1999) the ITER parameters were fixed with radii $R/a = 6.2\,\mathrm{m}$ $2.0\,\mathrm{m}$ and $B_T = 5.3\,\mathrm{T}$ as given in the second column of Table 1.1. The second major ITER group publication is Campbell, *et al.* (2001).

Campbell (2001) describes the final design of the ITER machine with major radius $R/a = 6.2\,\mathrm{m}/2.0\,\mathrm{m}$ and minor radius $a = 2\,\mathrm{m}$ and the mean toroidal magnetic field $B = 5.3\,\mathrm{T}$. The expectation is to achieve a plasma current $I_p = 15\,\mathrm{MA}$ and a fusion power amplification of $Q = 10$ from fusion power of $500\,\mathrm{MW}$.

The historical background of the design of ITER begins from the definitive fusion power experiments on the Tokamak Fusion Test Reactor that delivered the first deuterium-tritium experiments in 1993 and ran more than 840 DT discharges. The TFTR experiments were concluded in 1997. The first tritium experimental results in this relatively simple circular cross-section tokamak were reported by Bell, *et al.* (1989) at the International Atomic Energy Agency Meeting in Nice, France. A comprehensive review of the achievements of the TFTR experiments is given by Hawryluk (1998). The DT experiments were successful, producing a fusion power $Q_{\mathrm{fus}} = 0.5 \pm 0.13$ for pulses lasting a few energy confinement times. The TFTR plasmas reached record ion temperatures of $32\,\mathrm{keV}$ and thus high values of the fusion triple product of $n_e(0)\tau_E T_i(0) = 4 \times 10^{20}\,\mathrm{m}^3\mathrm{s\,keV}$ by using high-power neutral beam injection [Hawryluk (1998)]. These first DT experiments were performed in a hot ion mode called supershots as described in Chapter 6. The TFTR discharges, or "shots" as referred to in the laboratory, produced 10-12 MW of fusion power from injection of 40 MW of NBI power over period of half a second. The experiments were important for showing that in the fusion plasma there are alpha particle-driven MHD modes, or instabilities, that are excited by the high-energy (3.5 MeV) products of the fusion reactions [Nazikian, *et al.* (1997)]. Plasma instabilities excited by the 3.5 MeV alpha particles released in the fusion reactions place significant constraints on the ITER system as described in Chapter 2. The instabilities in the core plasma show up as structures called "fishbones" and "sawteeth", as explained in Chapter 3. The results of the TFTR experiments were largely incorporated in the design of the Joint European Tokamak or JET. JET began operation in 1991 [Jet Team (1992)] and achieved record fusion power gain Q_{DT} described in Keilhacker, *et al.* (1999).

A non-technical review of the history of the International Thermonuclear Experimental Reactor (ITER) is given by McCray (2010). McCray emphasizes three aspects of the project's history, focusing largely on the European research community's perspective. First, McCray explores how European scientists and science managers constructed a trans-national research community around fusion energy projects as part of Europe's larger technological integration and development. McCray (2010) expands on Gabrielle Hecht's concept of 'technopolitics' to the larger international dimension and explores how the political environments of the Cold War and the post-9/11 era helped shape ITER's history, sometimes in ways not entirely within researchers' control. The essay considers ITER as a technological project that gradually became globalized. At various stages in the project national borders became less important, while social, economic, legal and technological linkages created a shared societal space for fusion research on an expanding scale. Presently, ITER is an international treaty with seven countries working together. The project headquarters and building are on a plateau north of Aix en Provence adjacent to a the French nuclear laboratory called Cadarache with complementary nuclear facilities in Japan.

A popular account of scientists' 50-year quest to harness nuclear fusion as an energy source is described by Fowler (1997), who was leader of the fusion program at the Lawrence Livermore National Laboratory (LLNL). From the 1960-1985 the fusion research at LLNL centered on developing an alternative approach to fusion power based on the mirror confinement or mirror machine. This concept is still followed in two major nuclear laboratories, one in Tsukba, Japan, and the other at the Budker Institute for Nuclear Research in Novosibirsk, Russia. While reaching the fusion reactor power production with plasmas in a mirror machine is now considered as unlikely, the machine can be used as a compact source of fusion neutrons. These neutrons sources can be used for testing the lifetime of materials and for producing radio-pharmaceuticals for the diagnosis and treatment of cancers. Alternative approaches to fusion power are still actively pursued on small-scale machines.

At the 1997 time of Fowler, the four partners collaborating to build ITER were the European Union (EU), the USA, Japan and Russia. Fowler's evocative assessment: *'The sun never sets on ITER'*, became all the more salient after China, India, and South Korea joined the effort. By 2005, the mega-project represented over half of the world's population.

There is a qualitatively large extrapolation from JET to ITER. The Japanese Atomic Energy Research Institute (JAERI) designed and showed qualitatively new results in 1994 with knowledge that a design with an elliptical-shaped magnetic chamber, with two separate parts of the magnetic field configuration, would give better fusion engineering design features [Koide and JT-60U Team (1997)]. Koide introduced the term internal transport barriers to describe the new profiles of temperature and density with steep radial gradients outside the partial barrier zone discovered in Ishida, *et al.* (1997) and Koide, *et al.* (1998). The physics of these internal transport barriers is explained in Chapters 5 and 6.

Thus, both the JT-60U and JET machines were designed with plasma shaping poloidal field coils as shown in Figs. 1.1 and 1.2 that produce closed magnetic surfaces up to a certain radius of the plasma confinement region followed by an open magnetic field region between the metal chamber walls and the plasma confined inside the closed magnetic surfaces. This change in the magnetic field structure introduces what is called the magnetic separatrix (SX). A surface inside of which the magnetic field lines wind forever, in principle, around the magnetic axis in the core hot plasma region, and outside of which the twisting magnetic field lines terminate on the walls of the chamber, referred to as the divertor chamber. This structure allows the hot escaping plasma to be diverted into a special chamber designed to