*Relevance of Advanced Nuclear Fusion Research: Breakthroughs and Obstructions**

Bruno Coppi

Massachusetts Institute of Technology

An in depth understanding of the collective modes that can be excited in a wide range of high-energy plasmas is necessary to advance nuclear fusion research in parallel with other fields that include space and astrophysics in particular. Important achievements are shown to have resulted from implementing programs based on this reality, maintaining a tight connection with different areas of investigations. This involves the undertaking of a plurality of experimental approaches aimed at understanding the physics of fusion burning plasmas. At present, the most advanced among these is the Ignitor experiment involving international cooperation, that is designed to investigate burning plasma regimes near ignition for the first time.

*Sponsored in part by the U.S. Department of Energy.

1. Introduction

A puzzling question is why, after decades of research on nuclear fusion and highly significant advances made with it, an experiment capable of demonstrating the scientific feasibility of a self-sustained reactor has not been carried out. In fact, the often quoted promises of a fusion power producing reactor within 20 years were not made by scientists who had a sufficient in-depth knowledge of the importance of collective modes in determining the properties of fusion burning plasmas. The role of these modes has to be understood in order to conceive the construction of a significant fusion power station and proceed with it.

An aspect often overlooked is that the physics undertaking of the high pressure plasmas to be produced for fusion research is effectively transferable to other fields of physics and to high energy astrophysics in particular. Thus a special effort to maintain fusion research coupled to that of other relevant fields can be of mutual benefit and facilitate the advances of all fields involved. To outsiders, the coupling of research program motivated by two different needs, that of producing a novel source of energy and the other of attempting to understand the Universe, may seem extravagant but is well justified by our experience.

A parallel argument can be made for the wide spectrum of technologies developed in the past for fusion research and of those needed for further advancements. One of the best known cases is that of the LHC (particle accelerator) machine at CERN that employs super conducting magnets of the types developed earlier for fusion research.

The lack of understanding of these realities, and of the maturity of the field to proceed with experiments on fusion burning plasmas, by the entities in charge of fusion research in the richest countries of the world are the main reasons why this field has been kept from advancing at the rate and in the way that we had anticipated.

2. A Spectrum of Experimental Programs

Given the state of fusion research and the options of its advancements that are available, it seems appropriate that a spectrum of experimental programs be undertaken as exemplified by the following:

a. A program aimed at identifying the collective modes in a burning plasma close to ignition conditions. A program of this kind has to be based, in order to achieve its goals, on the high magnetic field technologies developed for the Alcator (MIT), Frascati Torus (ENEA) and Ignitor Programs. Ignitor is in fact the first machine designed with this objective.
b. A program on plasma confinement configurations sustained by the injection of high energy particle populations as pioneered by the GDT program Russia and the Tri-alpha program in the US.
c. A program aimed at producing nearly steady state configurations such as that developed by the Tokamak Energy group of the U.K.
d. A program aimed at developing the technologies needed to achieve significant fusion burn conditions for D-^{3}He and pure D plasmas.
e. A continuation of the existing programs on tridimensional (stellarator type) confinement configurations.

f. A more coordinated program than the existing isolated efforts on fusion with polarized nuclei given the advantages that this would offer.
g. An effort to integrate the Iter project with the outlined portfolio of programs offering valuable contributions to the physics of large volume plasmas.

Clearly, all of these programs involve considerable risks of failure but the benefits of possible successes and of technology and physics advancements that they can generate can justify their costs.

3. Nuclear Reactions and Ignition Conditions

The nuclear reactions that are considered for fusion research are as follows

D-T
D-^{3}He
D-D
p-^{11}B

Their properties are well known but the difficulties and advantages of employing them for fusion reactors are not equally well known. The DT reaction is the easiest to exploit in order to investigate the physics of fusion burning plasmas given its considerable reactivity at relatively low plasma temperatures. In reality the development of the high magnetic field technologies introduced in fusion research for the investigation of the fusion burn conditions of D-T plasmas can be extended to envisioned design experimental devices capable of exploring D-D and D-^{3}He burn conditions.

Referring to D-T plasmas, the reaction products are a neutron ($\mathcal{E}_n \simeq 14.1$ MeV) and an alpha particle ($\mathcal{E}_\alpha \simeq 3.5$ MeV). Ignition is defined as the condition under which energy associated with the produced α-particles and deposited in the plasma can compensate all forms of energy loss. An important requirement for this is that the burning plasma be relatively free of impurities as they increase the rate of radiation energy loss and in addition can lead to the excitation of impurity driven modes that can degrade energy confinement.

The thermal energy balance at ignition can be written roughly (the appropriate averages would need to be specified) as

$$n_D n_T \alpha_F \mathcal{E}_\alpha \langle \sigma_F \mathrm{v} \rangle = n_e \left(T_e + T_i \right) \frac{1}{\tau_E} \quad (1)$$

where α_F is the fraction of $\alpha -$particle energy deposited in the plasma column, $n_D = n_T = n_e/2$ indicate the particle densities, for the temperature of interest $\langle \sigma_F \mathrm{v} \rangle \propto T_i^2$ and τ_E is a global thermal energy confinement. Thus Eq. (1) leads to consider a parameter of merit

$$\mathcal{P}_M \equiv n\tau_E \frac{T_i^2}{\left(T_e + T_i\right)} \tag{2}$$

that (with appropriate averages) can be used as criterion for advancement toward ignition. Unfortunately, this is often used without considering other important parameters such as the degree of purity $\left(1/Z_{eff}\right)$, the partial degree $\alpha-$particle containment, etc. to classify the results of advanced confinement experiments relative to the goal of ignition.

An important intermediate goal to be reached is that of the ideal ignition condition, defined as that where $\alpha-$particle heating is sufficient to compensate the (unavoidable) bremsstrahlung radiation losses. This, for $T_e = T_i$, and $\alpha_F = 1$ corresponds to

$$n^2 \langle \sigma_F \mathrm{v} \rangle \simeq \alpha_B n^2 T^{1/2} \tag{3}$$

and, for a homogenous plasma, leads to a temperature of about 4.5 keV. After this condition is reached, the density with which a plasma column is heated can be raised without encountering a bremsstrahlung barrier. It is paradoxical that no experimental program before Ignitor was proposed had been undertaken to reach the limited goal of ideal ignition.

Now we must note that in a toroidal magnetically confined plasma, the maximum plasma pressure is related to the value of the parameter

$$\beta_p = \frac{8\pi n\left(T_e + T_i\right)}{B_p^2}, \tag{4}$$

where B_p is the poloidal component of the magnetic field. Then the reactivity $\mathcal{R}$ scales as

$$\mathcal{R} \equiv n^2 \langle \sigma \mathrm{v} \rangle_F \propto n^2 T_i^2 \propto B_p^4 \beta_p^2 \tag{5}$$

showing how important it is to devise experiments capable of sustaining relatively high poloidal fields. Likewise, the parameter of merit $\mathcal{P}_M$ scales as

$$\mathcal{P}_M \propto \beta_p B_p^2 \tau_E . \tag{6}$$

By considering the results of a variety of significant experiments we may take

$$\tau_E \propto I_p n^{\alpha_1} B^{\alpha_2} / T^{\alpha_3} , \tag{7}$$

where I_p is the plasma current producing the field B_p and B is the toroidal magnetic field, and obtain

$$\mathcal{P}_M \propto \beta_p I_p B_p^2 n^{\alpha_1} B^{\alpha_2} / T^{\alpha_3} , \tag{8}$$

where α_1 , α_2 and α_3 are positive numerical coefficients smaller than unity, pointing to a desirable direction that involves a combination of high currents and high poloidal fields [1].

As is well known there are stability considerations that link the maximum poloidal field to the toroidal field, the torus aspect ratio and other geometrical characteristics. The so-called "Iter Precipice" curve derived by various authors is an illustration of the scaling indicated by Eq. (5) as the poloidal field $B_p \propto I_p / \bar{a}$, $\bar{a}$ being a mean minor radius of the considered toroidal configuration. This curve shows that a decrease of the produced plasma current I_p, relative to that corresponding to the assumed minimal stability safety factor, results in a steep decrease of the generated fusion power. Clearly Eq. (8) does not point to the necessity of constructing large scale devices in order to advance the physics of fusion burning plasmas contrary to widespread information supplied to the public opinion.

Finally we note that, if ignition can be achieved, it becomes possible to investigate the onset and development of the so-called "thermonuclear instability" related to the fact that $\langle \sigma \mathrm{v} \rangle_F \propto T_i^2$. In fact, it has been shown that, as a result of the large values of the longitudinal to the transverse thermal conductivities, this instability can develop as a helical snake in a toroidal configuration [2].

4. High Energy Astrophysics and the Alcator Experimental Program

One of the main motivations for starting and developing the Alcator program in 1969 was that of producing and investigating plasmas with parameters close to those inferred for the plasmas surrounding the very few X-ray stars known at that time. In particular, the objective was to create low density plasmas characterized by non-thermal spectra, such as that of the Crab Nebula, and plasmas with very high densities, such as those associated with Cygnus X-1 the first X-ray object discovered (besides the Sun) and the resulting thermal spectra. In fact, Cygnus 1 inferred densities were in the range 10^{15}-10^{16} cm^{-3}, values that had never been produced earlier in a well confined plasmas.

To achieve these goals a toroidal machine featuring relatively high values of the ratio B/R, B being the toroidal field and R the major radius had to be devised. The solution for the high toroidal field was introduction of a toroidal magnet made of copper Bitter-plates alternated with steel plates by B. Montgomery.

However, the most difficult problem was that of inventing a completely new poloidal field system that would fit in a compact configuration and induce and sustain relatively high currents. In fact, the Russian tokamak solution was not appropriate for this purpose. Thus the "air-core poloidal field system" of the type represented in Fig.1 was invented [B. Coppi and B. Montgomery, 1969]. By now this system is adopted in all advanced toroidal confinement machines with an axisymmetric configuration including the largest machine under construction, Iter.

The first class of plasmas, non-thermal, were the first to be produced as they involved very low densities, in the 10^{12}-10^{13} cm^{-3} range. Then a new regime was discovered and analyzed consisting of a thermal and super-thermal electron populations created by the applied electric field $E_{\|}$ along the toroidal direction. In this regime [3], called "slide-away" two types of mode were found to be present: i) an electron scattering mode that would produce a pitch angle scattering converting electron parallel (to the magnetic field) energy into perpendicular energy; ii) a lower hybrid mode producing a non-thermal ion populations to which longitudinal electron enegry is transferred.

The second mode was later used to interpret the formation of ion-conics distributions in the auroral ionosphere [4]. The first mode had in fact been identified independently by V. Ginzburg in the context of cosmic ray physics. The analysis of the slide-away regime led to propose the first current drive process, called "slide-away regime in reverse" [5] whereby a lower hybrid mode is injected in a well confined plasma producing a current carrying super-thermal electron population. The current drive process for toroidal plasmas had later received extensive attention theoretically and has motivated a considerably large experimental effort.

The second class of plasmas required a considerable more effort to produce them. In the case of the Alcator-A machine the density could be raised to peak values around 10^{15} cm^{-3} by the gas valve technique which led to identify a new particle transport equation [6] that is not of the diffusive type. Later this led to identify a similar equation for the angular momentum transport that has been verified repeatedly by dedicated experiments [7] and is relevant to astrophysics [8].

The discovery of the high density regime [9] carried two surprises: one, that the relevant plasmas had a high degree of purity as realized first by S. Mirnov; the other that the energy confinement time was relatively high and it increased with density. These observations, led to the idea that a high field compact experiment could be devised in order to achieve ignition condition and initiated the Ignitor program. Clearly, the original motivations to produce plasmas with densities $n \sim 10^{15}\,\mathrm{cm}^{-3}$ came from Astrophysics but the end results turned out to be relevant to fusion research as well.

It may be worth mentioning the initial reactions that the idea of a compact ignition experiment derived from a small machine built in a university environment elicited. The large research outfits reacted with evident unease. The most benign comment was by an outstanding member (B.B. Kadomtsev) of the major Russian Institute active in fusion research who remarked that the idea was "worth a Nobel Prize but would not be of practical use". A fusion manager of the European Commission in Brussels felt that his career and retirement would be threatened by either a failure or a success of the experiment. Instead, the international academic community around the World reacted most favorably.

5. The Ignitor Program

As indicated earlier, the main objective of the Ignitor Program is to explore the ignition conditions of magnetically confined D-T plasmas while producing significant amounts of fusion power (up to about 100 MW). For this, a (necessarily) compact, high field device has been designed that advances the line of high field experiments which began with the Alcator program at MIT and was later also developed in Italy with the FT (Frascati Torus) program.

A short description and analysis of the machine core (see Figs. 1 and 2) has been given in Ref. [1]. A detailed design of all the main machine components has been carried out and its results and drawings are now ready to be transferred to the industrial groups that have been identified as capable of constructing all the components of the machine core.

The Ignitor facility is expected to be operated at the Troitsk (Moscow) site of Rosatom and managed by the IGNIR collaboration between Italy and Russia. At this time the Ignitor Program is the only one that has retained the objective of investigating the approach and the access to ignition conditions thanks to the regular updates of the machine design that have followed relevant advances in physics, technology and materials.

The most advanced set of machine parameters is given in Table 1. A major effort in the machine design has been that of producing a plasma column in which a high mean poloidal field $\bar{B}_p \simeq \sqrt{10}T$ can be reached together with plasma currents $I_p \simeq 10-11$ MA while maintaining reasonable safety factors against the onset of macroscopic instabilities (i.e. $q(\psi_a) \simeq 3.6$).

Sophisticated numerical simulations of the plasmas that Ignitors expected to produce have been carried out by 1+1/2 D transport codes [1, 10]. An example of a set of plasma parameters obtained by these simulations is given in Table II. In this connection we observe that well confined plasmas with maximum densities close to 10^{15} cm^{-3} have been obtained repeatedly by the Alcator line of experiments and, with lower temperatures, by the Large Helical Device machine of Japan. To facilitate the attainment of these densities, the adoption, as in the case of the Alcator C experiments, of a pellet injector is planned. In the case of Ignitor, however, the required pellet speeds are considerably higher and further advances (expected to be possible) in the technology of these injectors are needed.

An important additional criterion that has driven the Ignitor design process is that of having a strong Ohmic heating that would persist up to temperatures where α -particle heating can take over. Thus the need for an auxiliary heating system (ICRH is the only feasible option) is minimized together with the deterioration of the energy confinement time that has to be dealt with when Ohmic heating ceases to be significant. Assuming that the loop voltage is about constant, as has been observed experimentally until now, the best criterion to be followed in order to have a strong Ohmic heating rate is to have a major radius with the lowest possible values.

An essential requirement to achieve ignition condition is the degree of plasma purity that has to be high as discussed in Ref [1]. This restricts the spectrum of plasma regimes with which Ignitor has to operate in order to fulfill its main objectives. Therefore while following the progress made in analyzing various transport regimes the main attention remains devoted to the very high density so-called L-regime discovered originally by Alcator that can be reliably obtained and to the so-called I-regime that continues to be the subject of a series of investigations whose results are promising. In both regimes the observed degrees of purity are well within the limits required for ignition.

6. High Field Superconducting Magnet Technology, Second Stability Region and "Advanced" Fusion Reactions

Starting from a presentation on the Ignitor Program made at the 2002 Snowman meeting on the future of fusion research, the Program undertook the task of introducing high field superconducting magnet technology involving relatively large volumes into fusion research. The motivation is twofold. One is that a recently discovered superconducting material, Magnesium Diboride, has allowed the design of large size superconducting magnets operating at temperatures around 10 K. The development of these magnets has reached the point where they have substituted the two large vertical field copper coils in the design of the Ignitor machine. In addition, the bus bars for the LHC machine of CERN are made of this material and manufactured by the same company, Columbus of Genoa working on Ignitor. A pioneering toroidal machine involving high field superconductors had been constructed and operated earlier by S. Itoh at Kyshu University.

The other motivation is of a longer range nature. The limitation of using superconducting magnet the Ignitor only for the large vertical field superconductors of large volume has not progressed sufficiently to warrant their substitution to super cooled (30 K) copper magnets. Looking into future experiments where long pulses are required a solution that has been found promising is that of hybrid magnets. These consist of a MgB_2 magnet external component producing fields up to 10 T. The internal component that involves a smaller volume is envisioned to be “high” temperature superconducting magnet such as one made of REBCO with a configuration of the type suggested in Refs. [11, 2]. Clearly, when envisioning possible fusion power stations the development of high field superconducting magnets gives new and appealing perspectives. The structural solutions to deal with the relatively high stresses associated with high magnetic fields for present day experiments are expected to be suitable for more advanced experiments and, in case of success, of future power stations. In particular, the main structural solution adopted for the Ignitor machine is sketched in Fig. 4.

Plasma axisymmetric configurations of the type that can be produced with existing technology were found to have the possibility, through proper choice of their characteristic parameters, to enter the so-called “second stability region” [12]. In this region the confined plasma can reach finite values of $\beta \equiv 8\pi n\left(T_e + T_i\right)/B^2$ without exciting known macroscopic instabilities the best known of which is the “ballooning instability” [13] driven by the plasma pressure gradient. By combining this result with the perspectives opened by advancements in high field magnet technologies it became possible to identify for the first time [14] ignition conditions for D-^{3}He and D-D burning plasmas with realistic parameters for which a serious program of investigations can be conceived. Thereafter G. Miley analyzed envisioned scenarios of power producing systems involving D-D and D-^{3}He burning reactors that continues to deserve attention.

7. Conclusions

Fusion research has to deal with the reality (and responsibility) of not having yet investigated the physical properties of meaningful fusion burning plasmas. The relevant knowledge is necessary in order to proceed with conceiving and constructing realistic power producing fusion reactors. On the other hand the field (fusion research) is ripe with the developments of new technologies and new related ideas to justify a faster rate of progress than the one we are witnessing, with a more committed support and a deeper understanding by both the public and the private sector.

8. Acknowledgements

This paper is based on a presentation made at the opening of the symposium to honor the memory of Professor N. Rostoker held by the University of California at Irvine. Professor Rostoker in addition to being a brilliant and creative scientist had been a generous friend to me as well as a source of inspiration and encouragement that sustained me through my professional life. The presented work was sponsored in part by the U.S. Department of Energy.

9. References

[1] B. Coppi, *et al*., *Nucl. Fus*. **53**, (2013) 104013.
[2] B. Coppi, *et al., Nucl*. Fus. **55**, (2015) 053011.
[3] B. Coppi, F. Pegoraro, R. Pozzoli, G. Rewoldt, *Nucl. Fus.* **16**, (1976) 2: 309-328.
[4] T. Chang and B. Coppi, *Geophys. Res. Lett*. **8**, (1981) 1253.
[5] B. Basu and B. Coppi, MIT/RLE Report PRR-76/4 (1976).
[6] B. Copp and C. Spight, *Phys. Rev. Lett*. **41**, (1978) 551.
[7] K. Nagashima, Y. Koide, H. Shirai, *Nucl. Fusion* **34**, (1994) 449.
[8] B. Coppi, *Plasma Phys. Control Fus.* **36** (1994) B107.
[9] E. Apgar, B. Coppi, *et al*. *Plasma Physics and C.N.F. Research* **1**, (1976) 247.
[10] A. Airoldi, G. Cenacchi, *Nucl. Fus*. **37**, (1997) 1117.
[11] B. Coppi and L. Lanzavecchia, *Comments Plasma Phys. Control. Fusion* **47**, (1987) 11.
[12] B. Coppi, J. Ramos, A. Ferreira, *Phys. Rev. Lett*. **44**, (1979) 990.
[13] B. Coppi, M.N. Rosenbluth, S. Yoshikawa, *Phys. Rev. Lett*. **20**, (1967) 190.
[14] B. Coppi, *Physica Scripta*, T2/2, (1982) 590.

2. Vertical cross section of the Ignitor ine as presently designed.

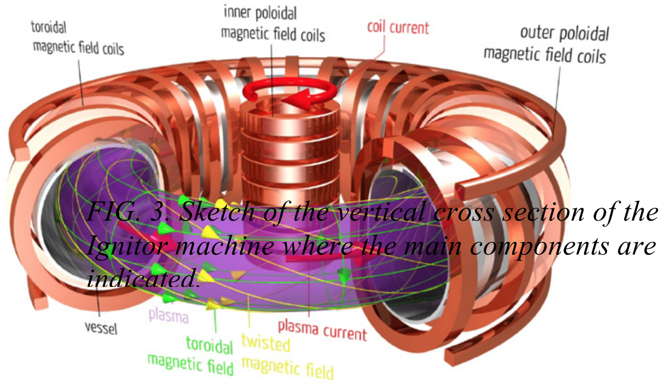
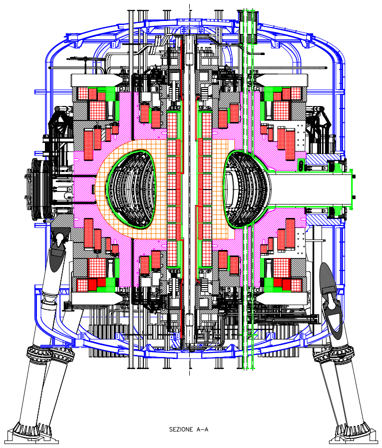
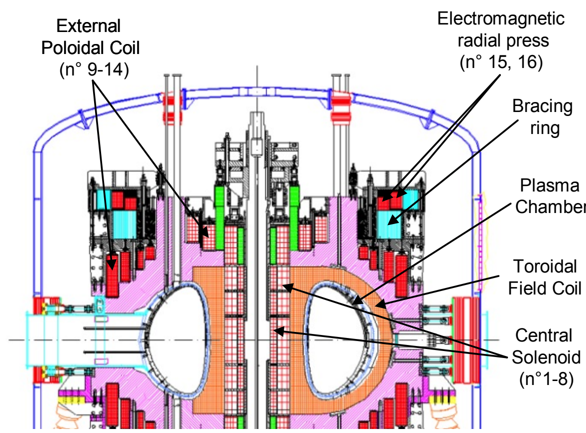


FIG. 3. Sketch of the vertical cross section of the Ignitor machine where the main components are indicated.

FIG. 1.





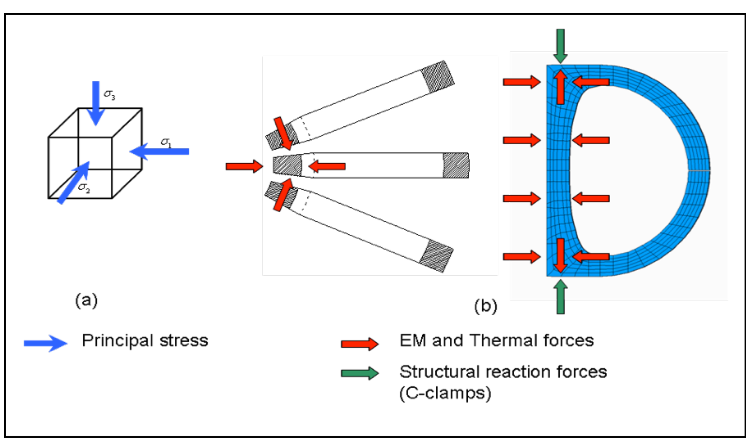


FIG. 4. "Bucking, Wedging and Bracing" structural solution for the toroidial magnet. The objective is to minimize the unbalance between the principal stress components

FIG. 5. View from above the core of the Ignitor machine. Reprinted on the cover of a recent volume of Nuclear fusion.

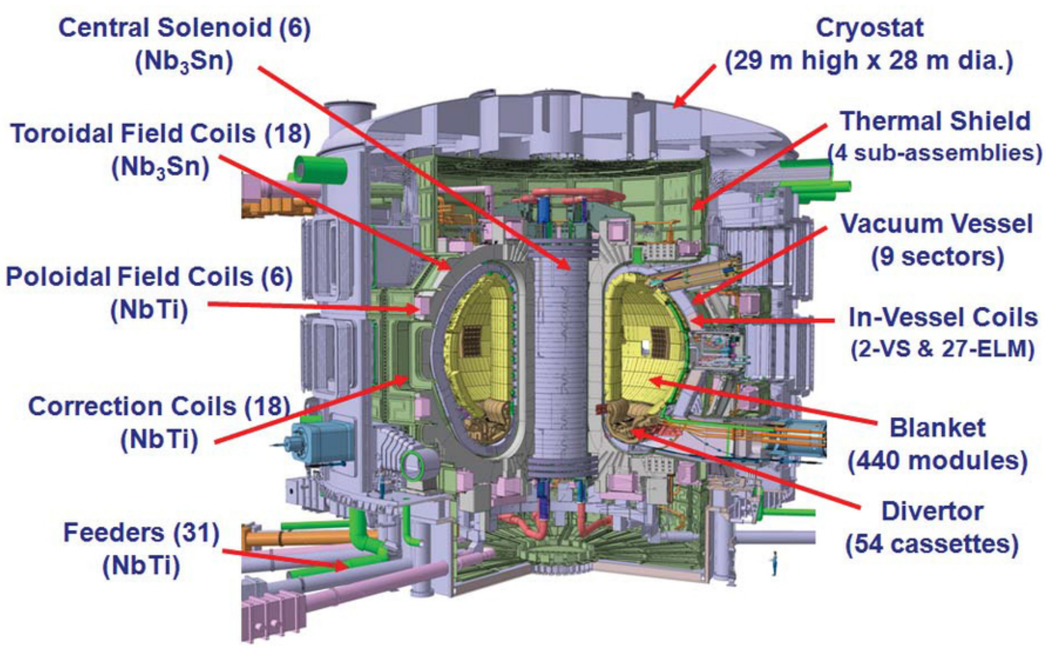


FIG. 6. Schematic diagram of the components of the ITER tokamak

Table I: Main Design Parameters

Toroidal plasma current I_p (MA)	11
Toroidal field B_T (T)	13
Major radius R_0 (m)	1.32
Minor radius $a \times b$ (m^2)	0.47 × 0.86
Elongation κ	1.83
Triangularity δ	0.4
Plasma volume V_0 (m^3)	10
Edge safety factor $q_\psi = q_\psi(a)$	3.5
ICRF power P_{ICRH} (MW)	6.4→12.8
Poloidal plasma current (MA)	≅8.4
ICRH Pulse length (s)	4

Table II: Example of Plasma Parameters Obtained with Modest ICRH Power (JETTO codes [10])

Toroidal plasma current I_p (MA)	10
Toroidal field B_T (T)	13
Major radius R_0 (m)	1.35
Minor radius $a \times b$ (m^2)	0.46 × 0.80
Elongation k	1.74
Triangularity δ	0.44
Plasma volume V_0 (m^3)	8.7
Edge safety factor $q_\psi = q_\psi(a)$	3.5
Central electron temperature T_{e0} (keV)	15.8
Central ion temperature T_{i0} (keV)	13.6
Central electron density n_{e0} (m^{-3})	8.7×10^{20}
Alpha density parameter n^*_α (m^{-3})	2.3×10^{18}
Fusion alpha power P_α (MW)	19.8
Plasma stored energy W (MJ)	11.5
OH power P_{0H} (MW)	3.5
Bremsstrahlung power loss P_{brem} (MW)	2.3
Poloidal beta $\langle\beta_p\rangle$	0.22
Toroidal beta $\langle\beta_T\rangle$ (%)	1.2
Bootstrap current I_{bs} (MA)	1.1
Energy confinement time τ_E (s)	0.58
Alpha slowing-down time $\tau_{\alpha,sd}$ (s)	0.09
ICRF power P_{ICRH} (MW)	2.2
Poloidal plasma current (MA)	7.9
ICRH Pulse length (s)	1.3