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ITER—An Essential Step Toward Fusion Energy

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Figure 1: Picture of the ITER site

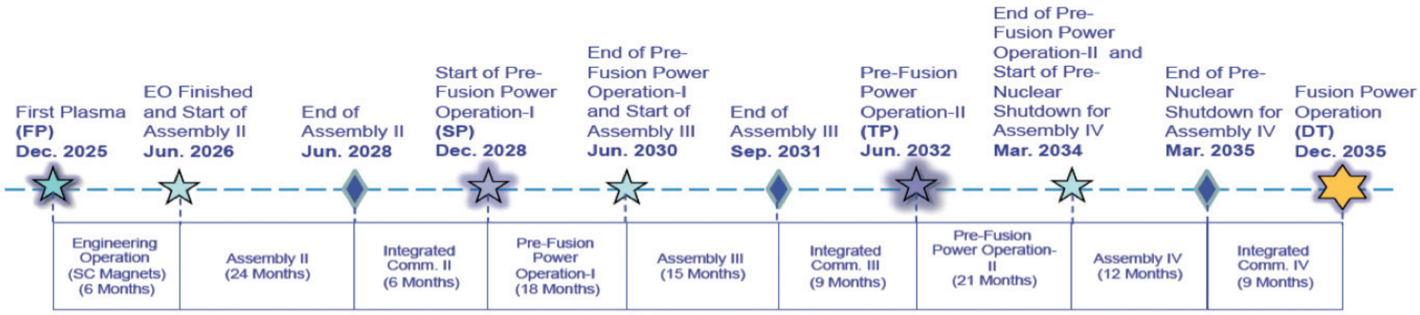
Fusion reactions hold enormous potential for clean, sustainable energy production from more equitably distributed resources, but a demonstration of technical and economic viability remains to be carried out. The ITER tokamak[1], now under construction in France, represents an essential step toward a practical technical demonstration of fusion energy. The Project Specifications set specific goals this step: 500 MW of fusion power with a power gain Q (ratio of fusion power to input power) of 10 for at least 300 s and in-principle steady-state operation with Q = 5. These goals place ITER at the threshold of the conditions suitable for baseload power plant operation, consistent with the goal of minimizing physics uncertainty in the next-step device, which would be a prototype power plant.

The ITER Organization is charged with the construction and exploitation of the tokamak. It is the result of a Joint Implementing Agreement of China, the EU (through Euratom, so including Switzerland), India, Japan, Korea, Russia, and the US. Nearly 90% of the components required for the tokamak and balance of plant are supplied through in-kind contributions by Domestic Agencies formed by the Members for this purpose.

1 For a description of the ITER («the way» in Latin) see https://www.iter.org/

In November 2017, the 50% completion point for activity required for First Plasma (design, fabrication, assembly, and commissioning) was passed. In the last three years, most of the buildings seen in the site (photograph above) have been constructed and installation of many plant systems has begun. Progress is accelerating toward the achievement of First Plasma, scheduled for the end of 2025.

In order to reach the fusion conditions specified above, ITER will be fueled with a nearly 50-50 mixture of the two heavy isotopes of hydrogen, namely, deuterium (D) and tritium (T). The fusion reaction between these two isotopes has the highest cross-section at temperatures readily achievable even in present-day tokamaks (1-2 · 10^8 K). The D-T reaction has two by-products—a neutron with 14.3 MeV energy that contributes to volumetric heating of the blankets surrounding the plasma and an alpha particle with 3.4 MeV energy that slows down within the plasma for 'self-heating'. In addition to the distributed heating from the 14.3 MeV neutron, reactions of these neutrons with lithium in the blankets in future fusion devices will be used to breed the tritium fuel needed, since tritium does not occur in significant quantities in nature due to a relatively short half-life (12.3 years). Prototypes of these tritium breeding systems will be tested on ITER, but not of sufficient size to breed its own fuel.



Reaching the fusion goals specified above will require a substantial technical commissioning and physics research effort. There are two major phases of operation—Pre-Fusion Power Operation and Fusion Power Operation. An overview of the schedule following First Plasma up to the beginning of the first Fusion Power Operation campaign is shown below.

A brief discussion of the objectives of each part of the schedule is given here. The full details are in the ITER Research Plan, which has just been released as an ITER Technical Report (*https:www.iter.org/technical-reports*). In the Pre-Fusion Power Operation (PFPO) phase, consisting of two campaigns, only hydrogen or helium fuel will be used. This limits the neutron generation to very low levels, allowing personnel access to tokamak building to maintain the equipment during this phase of commissioning.

At First Plasma, the basic components of the tokamak, the magnets and the vacuum vessel, will be demonstrated to function together as intended. This is the culmination of a year-long 'Integrated Commissioning' of the tokamak assembly and the basic plant services required to make plasma. The goal is >100 kA plasma current for >0.1 s. These are modest compared to the baseline design of 15 MA plasma current and the possibility to sustain lower plasma currents for as long as 3000 s, but the purpose is primarily to commission the tokamak assembly. Following First Plasma, commissioning activities continue for six months of Engineering Operation, including taking the toroidal field magnets to full design parameters (5.3 T).

After this, the in-vessel components to handle the high heat and particle fluxes and protect the vacuum vessel and magnet from the plasma will be installed. When complete the first of the PFPO campaigns will focus on the commissioning of the basic controls and protection systems required for later phases. One of the three heating systems (20 MW of electron cyclotron heating at 170 GHz) will be fully implemented and commissioned. Thus it will be possible to initiate modest physics studies, primarily focused on comparing the achieved plasma confinement to the predicted values.

In the next shutdown, the full complement of heating systems will be installed (33 MW of negative-ion-based neutral beams at 1 MeV and 20 MW of ion cyclotron heating at 40-55 MHz), as will nearly all of the diagnostics. The main goal of the following PFPO campaign is to fully commission the heating systems and qualify all of the controls and protection systems up to full plasma current. All major systems and controls needed for the Fusion Power Operation (FPO) phase should be tested by the end of this phase. While the main focus is again on system commissioning in this phase, a modest physics research program will be possible.

In the last assembly phase prior to FPO, the last major system, the tritium processing plant, will be completed and commissioned. Upon receipt of a license from the French nuclear regulator, the FPO campaigns can begin. At this point, the research program focuses on the Project goals introduced above. In the first FPO campaign, the focus will be on reaching transiently (~50 s) the 500 MW at Q = 10 goal. When successful, this will be the first time that dominantly self-heated or 'burning' plasmas have been produced in a tokamak. In the second FPO campaign, the research program will focus on extending the burning plasma regime to >300 s and initiating the research on steady-state plasmas that have large self-heating for up to 3000 s. In the third campaign, optimization of the steady-state scenario pointing toward Q = 5 will be the focus. Following this, the facility has significant design lifetime that can be used for fusion physics or technology research, depending on the results of the first campaigns and the interests of the ITER Members.

Achievement of the ITER Project goals will be a landmark in the quest for energy production from fusion. The vision of the fusion community is that it will be analogous to the flight of the Wright brothers to the aviation industry—a proof of principle that both establishes a vision for what is physically possible and a trigger for technological innovation and development leading to the rapid industrialization of fusion for energy production.