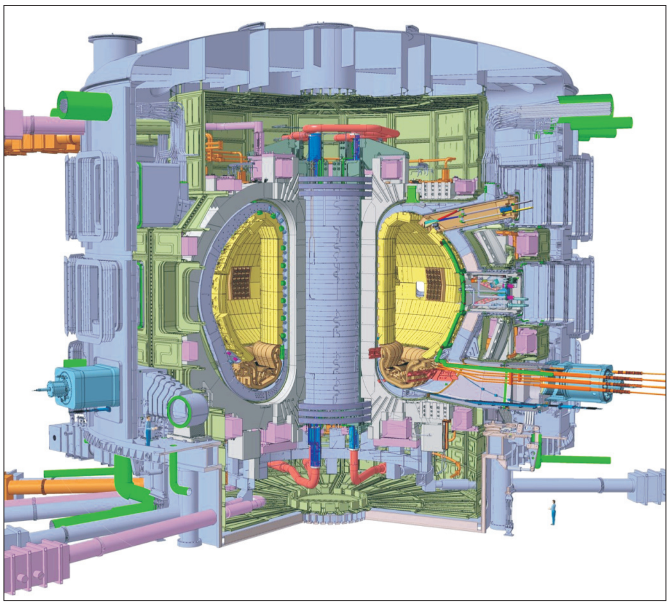
Focus on nuclear fusion research

Institute of Plasma Physics AS CR, v.v.i., Za Slovankou 1782/3, Prague 8

Future of the energy production is a critical challenge, in particular with respect to the requirements of sustainable development. Based on our current knowledge there is no singular power source that could cover the increasing energy demand with acceptable consequences to our environment. Therefore, significant research efforts towards development of a broad portfolio of sustainable power sources are necessary. In this framework, nuclear fusion offers a rather unique promise of a powerful, safe and sustainable base-load source with abundant fuel supply. An overwhelming proof is demonstrated by nature: nuclear fusion is the power source of stars, including our Sun. Although only one billionth of solar power targets the Earth, it has been sufficient and stable enough to sustain life and water cycle on our planet for billions of years. Ever since the first hypothesis appeared on the fusion origin of this immense power source (by Sir A.S. Eddington in 1920) the humankind has been intrigued by a possibility of mastering nuclear fusion reactions for our welfare. The only caveat is that the required reactor conditions – in particular very high temperatures, sufficient fuel density and good heat insulation – are extremely demanding for our present technologies. However, as the stakes are increasingly high and the engineering is getting ready, the international community decided to extrapolate the current experimental results to a reactor scale and started construction of the first nuclear fusion reactor ITER.



A cutaway view of the future ITER Tokamak
(Courtesy of ITER Organisation)

ITER – the international fusion reactor

In ITER, technologies of the future fusion power plants shall be tested and optimised. The reactor is designed to produce 500 MW of fusion power in experiments lasting several tens of minutes. Commissioning of main parts is expected in 2019 and full fusion power in approximately 2025. While ITER is foreseen to be a flexible experimental facility focused on R&D tasks, the subsequent project DEMO is presently being designed as a demonstration power plant, with net electrical power production and a simplified, robust construction. Provided that this roadmap is successfully followed, fusion may become an influential player on the energy market in the second half of this century.

ITER machine is a large superconducting device of the tokamak type. In tokamaks, very high temperatures are insulated from our “cold word” by a poweful magnetic field. Indeed, the fuel at the required extreme temperatures of more than a hundred million Kelvin is in the state of fully ionised gas, which is referred to as high temperature plasma. Instead of neutral molecules and atoms, high temperature plasmas consist of separate nuclei and electrons. The charged particles stick to magnetic field lines, so that plasma is confined by magnetic field. Technically achievable magnetic fields - several Teslas - can confine plasma pressures of up to several bars (10^5 Pa). As pressure is proportional to product of density and temperature, it can be directly seen that plasmas in tokamaks (including ITER) must be very rare, with densities of approximately one millionth of the air density. This is a key safety feature of the proposed fusion reactors; it means that the burning plasma, albeit at extremely high temperature, does not contain substantial thermal energy. Notice that fusion is a burn process, so that unlike in chain reactions there is no critical mass of fuel - fusion can run on an arbitrary low amount of fuel provided that the burn conditions are met. Indeed, only a few grams of fuel will be present in a fusion reactor at any time.

A mix of heavy isotopes of hydrogen - deuterium and tritium - features the highest fusion reactivity and therefore it serves as the fuel of the first generation of fusion reactors including ITER. Deuterium is a natural isotope that can be readily separated from water. Tritium shall be produced from lithium due to neutron capture in the reactor shell known as blanket. Technology development of the tritium breeding blanket is one of the key missions of ITER. In fusion reactions of deuterium and tritium, helium nuclei and neutrons are produced together with large amount of energy. The helium nuclei are confined by magnetic field so that their kinetic energy helps to sustain high plasma temperatures against plasma power losses. The neutrons hit the reactor shell (the blanket) where their kinetic energy is transferred into heat. In fusion as well as in fission, the key merit of harnessing nuclear power lies in the extremely low fuel consumption – it is sometimes mentioned that lithium in one laptop battery complemented with deuterium from half a bath of water would in a fusion reactorenoug produce energy for an EU citizen for more than five years.

ITER is being built at Cadarache in southern France by seven Members: the European Union, Japan, the Russian Federation, USA, People's Republic of China, Republic of Korea and India. The European Union, being the host of ITER, is also its major contributor. The in-kind contributions and ITER related R&D are co-ordinated by Domestic Agencies of the seven Members; in the EU this role belongs to the agency Fusion for Energy (F4E) located in Barcelona, Spain.

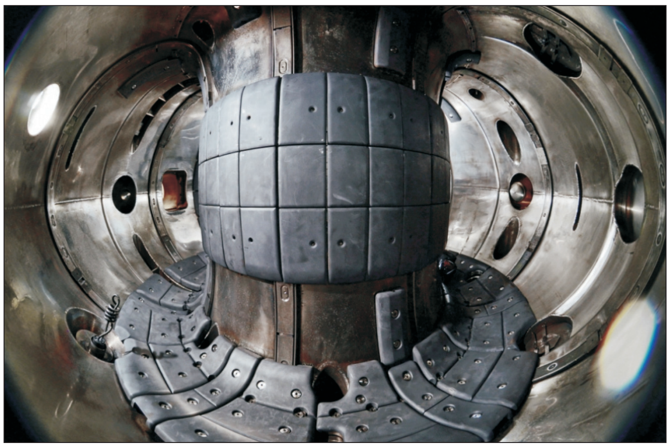
The Czech contribution

The extremely strong position of Europe in the ITER project is due to the tradition of close co-operation and coordination of fusion research activities among many European research institutes associated under EURATOM. The Institute of Plasma Physics of Academy of Sciences of the Czech Republic (IPP Prague) signed the “Contract of Association” at the end of 1999, with the goal to integrate the Czech Republic into the European fusion research programmes. This agreement established the Association EURATOM - IPP.CR which now coordinates the research in the field of nuclear fusion in the Czech Republic as well as the international collaboration with other EURATOM Associations. However, history of fusion research in IPP Prague dates back to

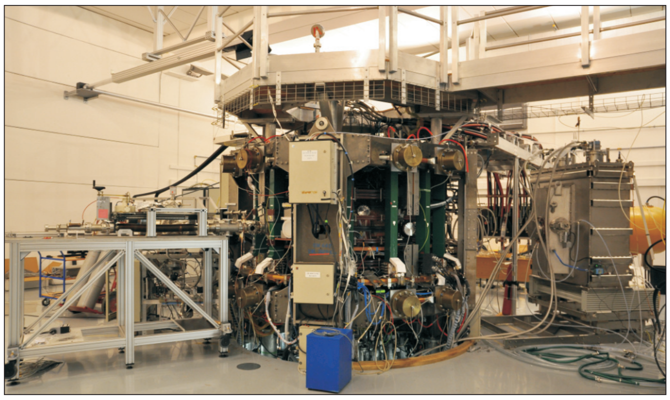
1960s, when significant contributions to theory on plasma-wave interactions were developed in the institute. Based on this success, our experts were backed by the Moscow Kurchatov institute who donated us a small tokamak TM1-MH in 1977. This machine, later renamed to CASTOR, had been operating in Prague for thirty years. As a matter of fact, the Czech Republic - from the viewpoint of fusion research - had a privileged place among the 10 countries that joined the EU in 2004: it was the only new EU member state with an operating tokamak. CASTOR underwent several upgrades, but it was rather small and lacked several critical components, such as a divertor – a key part of a modern tokamak that acts as a plasma exhaust – which meant that the machine was incapable of carrying out research relevant to the ITER related challenges.

Just as the Czech Republic was joining the EU, a tokamak known as the Compact Assembly (COMPASS) at the UK Fusion Association (today's Culham Centre for Fusion Energy, CCFE) was under offer to other Associations in order to pave the way in Culham for a more ambitious UK project – the Mega Amp Spherical Tokamak MAST. Importantly, tokamak COMPASS is far from outdated. It contains a D-shaped vacuum chamber with a divertor, which means that experiments performed on COMPASS can be scaled up to mimic plasmas characteristic of those planned for ITER. In other words, high temperature plasmas in COMPASS look like approximately 1:10 scale model of the ITER plasmas, so that the smaller machine can serve as a "wind tunnel" predicting behaviour of large facilities. The corresponding research tasks are related in particular to turbulent transport of heat and particles in the plasma, where numerical modelling fails to give reliable predictions.

The bold project of reinstallation of the COMPASS tokamak in Prague eventually received all necessary financial support from the Czech government as well as priority support from EURATOM. The machine was moved to IPP Prague in October 2007 and as soon as in December 2008 it had demonstrated a plasma discharge. Notice that most of the auxiliary systems for the facility must have been designed and built on site. To start with, COMPASS requires up to 50 MW electric power in 2 second pulses. Unlike in CCFE, in IPP Prague this power level is not available from the grid so that two flywheel motor-generators capable of producing 35 MW each had to be procured and installed. A brand new control and data acquisition system had to be commissioned and all major systems for measurements the plasma performance (plasma diagnostics) had to be designed. Many of these diagnostic systems are being finalised and tested now, including a Thomson scattering system for measurements of plasma electron temperature - the first of its kind in the country. Several diagnostic systems have been installed by collaborating Associations, in particular by our Hungarian colleagues. Another important upgrade involves brand new systems for heating the plasma by a beam of fast hydrogen atoms. The beam injection will result in reaching considerably higher ion temperature in



A view into the plasma chamber of the COMPASS tokamak



The COMPASS tokamak in IPP Prague contributes to the ITER-related fusion research

COMPASS, up to several tens of millions of Kelvin. The two systems for neutral beam production, built by Budker Institute of Nuclear Physics, Novosibirsk, Russian Federation, were commissioned in IPP Prague in April 2011.

The COMPASS tokamak with its young and motivated team is currently the only major ITER-relevant fusion research infrastructure in the new EU countries. Therefore the facility aspires to become a regional centre for both cutting edge fusion science and advanced training of new fusion experts, who may in future contribute importantly to the research both at home and in international fusion centres including ITER. To this end, regular international summer training schools SUMTRAIC are organised on COMPASS and a wide co-operation with several universities has been established. The former CASTOR tokamak was donated to the Czech Technical University where it is reinstalled as the GOLEM facility, serving the Master students in their practica and featuring an increasingly popular option of remote participation.

Concerning our research programme in IPP Prague, experimental works as well as considerable efforts in computer modelling are dedicated in particular to three fields of nuclear fusion research: edge plasma physics, interaction of plasmas with electromagnetic fields, and development of advanced diagnostics. Besides exploiting the COMPASS tokamak we also participate in experimental work of other European facilities including, for example, tokamaks JET, ASDEX-U and TORE SUPRA. Together with other members of the Czech association we also reinforce our participation in the engineering research, in particular focused to the development of the reactor–grade materials.

Concluding remarks

The ITER machine will integrate more than one million hi-tech components, including world largest superconducting coils and world largest vacuum vessel. The ITER project actually presents the second biggest endeavour of the international scientific co-operation after the International Space Station (ISS) and surpassing the Large Hadron Collider in CERN. None of these large centers of cutting-edge research would be feasible without a broad international co-operation. We feel privileged that research scientists and expert technicians of IPP Prague are well integrated into the fusion quest and therefore can directly contribute to the development of one of the most prospective power sources of the future.

References

For detailed information on the advances of international fusion research the following webpages are recommended: the ITER Organisation webpage http://www.iter.org/ and the webpage of the European agency F4E http://fusionforenergy.europa.eu/. More information on the Czech COMPASS tokamak can be found on webpages of IPP Prague: http://www.ipp.cas.cz/

Ing. Petr Křenek CSc., and RNDr. Jan Mlynář Ph.D.