MODELING AND SIMULATION NEEDS IN FUSION ENERGY RESEARCH

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ABSTRACT
Fusion energy research has reached a state, where a transition from laboratory scale physics experiments to industrial scale reactors has become possible. Current devices can routinely reach plasma conditions needed for a fusion reactor, but positive energy balance can only be achieved after a further increase of the machine size by about a factor of two (compared to the currently largest device – JET – in Culham, UK). Although this step seems to be straightforward, it involves some remarkable qualitative changes relative to present day devices: dominance of plasma self-heating by alpha particles, huge neutron load on all components, activation of the structural materials, etc. This paper gives an overview on the status of fusion research, key components of a fusion reactor and simulation possibilities and needs in the hope that modelers in other fields can contribute to the development of fusion energy.

Keywords: fusion energy, confinement, large scale modeling, tokamaks, ITER.

1. INTRODUCTION

Since the discovery of nuclear reactions, controlled nuclear fusion has been considered as a great opportunity for energy production. Unfortunately, fusion reaction occurs only if the nuclei approach each other much closer than their own size. Moreover, due to their identical electric charge, nuclei repel each other, and the requirement for a fusion even to take place is that the particles have enough kinetic energy to overcome the repulsion. The necessary energies for the fusion of protons are in the 10 keV (kilo electronvolt) range.

Such energies can easily be achieved for example in an accelerator, therefore nuclear fusion reactions had already been studied in detail some 50 years ago. From these measurements we know that the reaction cross-section of fusion processes is so low compared to Coulomb scattering, that a fast particle beam spends most of its energy for heating the target and the net energy gain from fusion reactions in accelerator driven systems is in the 1% range.

The situation is completely different when considering a high temperature medium with mean particle thermal energies in the 10 keV range. Under such conditions collisions are necessary to only maintain the thermal equilibrium and every fusion reaction provides net energy production. Ten kilo electronvolt thermal energy corresponds to about 100 million °C, and thus in the devices for fusion energy production matter needs to be heated and sustained at these extreme temperatures.

Among various possible reactions the fusion of Deuterium and Tritium into Helium and a neutron (DT reaction) occurs at the lowest threshold energy. This reaction releases about 17 MeV energy, of which 14 MeV (80%) is carried away by the neutron. This energy per fusion reaction is very high and for a 1GWe power plant only a couple of hundred kg of fuel material would be needed annually. As for the fuel materials, Deuterium is abundant on Earth but Tritium is practically not available. To produce the necessary Tritium one can make use of other nuclear processes, where Tritium is generated from Lithium nuclei using the neutrons released in the fusion reactions. Using a combination of these processes the scheme of a fusion reactor can be established as shown in Fig. 1.

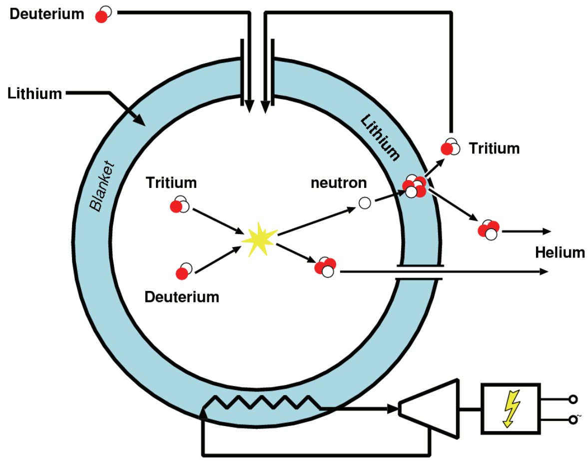

Figure 1: Theoretical scheme of a fusion reactor.

As it can be seen, the reaction chamber is surrounded by a blanket, in which the Tritium is bred. The input is only Deuterium (e.g. from water) and Lithium (e.g. from the Earth's mantle), and the output is Helium. Some neutron multiplication materials (e.g. Lead or Beryllium) are also needed to replace the neutrons inevitably lost in nuclear reactions with the structural materials. Some nuclear waste would be generated in these latter reactions, but their amount can be limited by a careful choice of the structural materials and their radioactivity would completely decay in about 100 years. Therefore fusion reactors would be environmentally benign, since *both their fuel and their waste are not radioactive*.

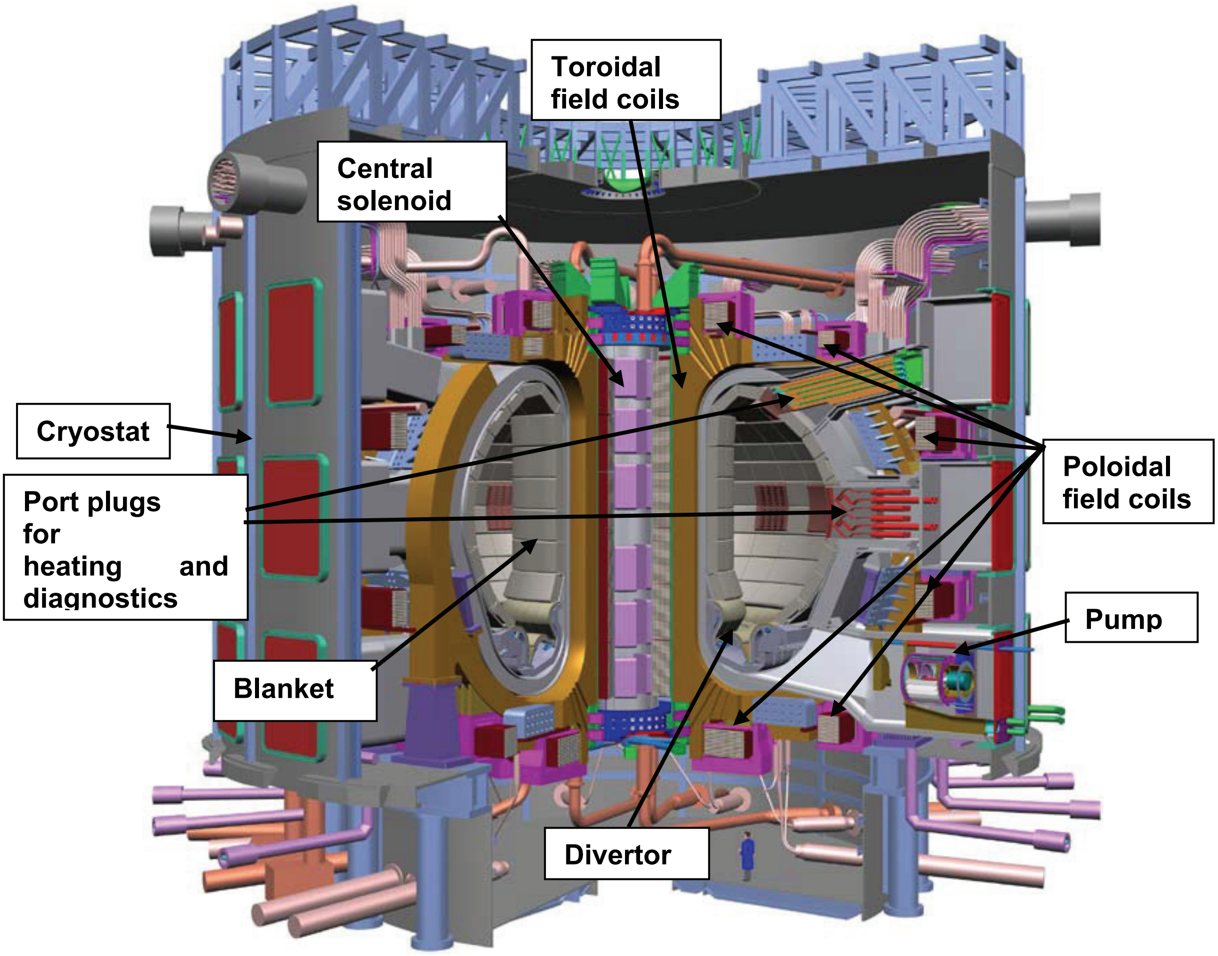

Figure 2: Design of ITER. The key components of a tokamak device are also shown

2. THE STATUS OF FUSION RESEARCH

The above theoretical scheme can be implemented in two ways: by micro-explosions in the chamber (inertial confinement, ICF) or by magnetic confinement of the hot plasma. During the past 5 decades both concepts went through a series of detailed physical experiments, and reached the status where the next generation devices are expected to show positive energy balance. In the case of ICF this will be achieved in single explosions, releasing little energy and the extrapolation to high-frequency (about 10 Hz) repetitive operation still demands substantial technical development for the cost effective and reliable manufacturing of the capsules and operation of driver devices like laser or particle beams.

Magnetic confinement fusion reached a state, where the design of a reactor scale experiment became possible. The International Experimental Thermonuclear Reactor (ITER, ITER 1999) is expected to deliver 500 MW fusion power in discharges up to 1000 s in length. This device will not be a power plant, but rather an experiment and will hopefully provide the physical and technical basis for one or more demonstration fusion reactors, like DEMO (EFDA 2005). Due to their large size and extreme complexity, construction of each of these devices will last at least 10 years and experiments will also take decades. To shorten this time and increase the reliability of the experiments, modeling of all structural components is an absolute necessity.

Compared to previous magnetic fusion devices, ITER represents a major challenge and calls for a cultural change. Up to now experiments were mostly designed and operated by physicists and the major design aspect was flexibility. Although reliable operation of major components was necessary, it was always possible to react to unforeseen problems and new ideas in a flexible way. In ITER the situation will be quite different. The device will be a nuclear installation, therefore safety, licensing, reliability and remote handling becomes critical. Once built, any change to the device (even smaller diagnostic elements) becomes extremely cumbersome and time-consuming. The necessary reliability calls for quality assurance and detailed modeling of all possible operating scenarios. Magnetic fusion research faces a transition from physics research to industrial technology development.

3. STATUS OF COMPONENTS AND KEY TECHNOLOGIES

3.1. Plasma confinement

At 100 million °C temperature the mean kinetic energy of the gas atoms is well above the binding energy of the electrons, therefore the atoms are completely ionized, i.e. the ions and the electrons form a plasma. The basis of confinement is the fact that a magnetic field forces the particles onto spiral trajectories around the magnetic field lines. As movement along the magnetic field is free, such a configuration must be used in which field lines are not leaving the plasma. The only topological arrangement fulfilling this criterion is a torus. For a good confinement, the field lines not only need to lie on toroidal surfaces, but also need to cover it sufficiently dense. The resulted configuration is a set of nested magnetic surfaces with helical magnetic field.

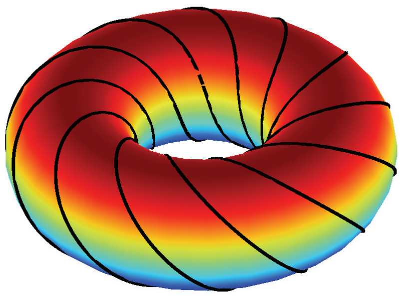

Figure 2: Illustration of field lines and magnetic surfaces in a toroidal confinement device.

There are several ways to create this plasma configuration, the most advanced concept being the tokamak as shown in Fig. 2. The main (toroidal) component of the magnetic field is provided by external coils (toroidal field coils), while winding of the field lines onto tori is done by the magnetic field of a strong current in the plasma itself. In magnetic confinement the kinetic pressure of the plasma is compensated by the magnetic pressure. Since the field strength is limited by cost and technology and the plasma temperature requirement is also given, the plasma density must be limited to values about 10^{-5} times the atmospheric density.

Plasma force equilibrium is very well described by magneto-hydrodynamics (MHD) if the transport coefficients (heat conduction, particle diffusion, etc) are known. For the plasma equilibrium some additional magnetic field components are required, and these are generated by the poloidal field coils.

There is a large variety of waves in plasmas, which – besides MHD – often involve kinetic or even single particle motion effects. Although these waves can be rather complex, they can be individually described with reasonable accuracy. The energy and particle losses of the plasma through radiation and charge exchange can also be well calculated. Despite of these encouraging results, transport losses (e.g. heat and particle diffusion) are not fully understood. So called neoclassical transport theory, describing transport via single particle motion and collisions agrees with experiments neither in the order of magnitude nor in trends. It is believed that effective transport is driven by micro-turbulence in the plasma involving a spatial scale of 2 3 orders of magnitude below the machine size, and a temporal scale of 4 5 orders of magnitude below the global transport timescale. Most recent experiments and theories show, that turbulence is highly nonlinear and involves interaction between different structures, waves and profiles.

Bifurcations are often observed in the experiments providing different plasma operation modes. Although simulations and experiments have agreed on some basic features and mechanisms in micro-turbulence (PPCF 2006) it is currently not possible, and will most probably not be possible in a decade, to describe plasma transport in a predictive way.

To overcome the lack of a predictive theory, plasma confinement scaling laws have been established. These describe global confinement properties and other global parameters in the form of a power function of various machine and plasma parameters. Constants of the scaling laws are fitted by regression to data from a carefully selected set of comparable measurements on various devices. It is encouraging, that e.g. the effective transport loss in various experiments can be fitted over 2 orders of magnitudes with an accuracy of a factor of two. These scaling laws give the basis of the ITER design with a good reliability.

It has to be noted that besides the most advanced tokamak concept, some alternative toroidal devices are also being developed. The compact tokamak promises higher plasma pressures and increased plasma volume compared to the device size. Various stellarator concepts provide the helical twist of the magnetic configuration via a helically distorted geometry. This solution does not need plasma current and avoids all problems associated with it (see a next section), therefore the stellarator concept can easily be extrapolated to continuous operation. Modern numerical simulation techniques enabled optimization of the inherently three-dimensional stellarator configurations according to various parameters and a wide variety of configurations are being tested in various laboratories, including two large superconducting machines: the already operating Large Helical Device in Japan and the innovative Wendelstein 7 X device under construction in Germany. For an overview of fusion research see Braams and Stott 2002.

3.2. Magnets

In today's fusion devices magnets are usually made of copper conductors. Although they fit to the short pulse lengths (< 1 minute) needed for physics experiments their excessive power dissipation makes them unsuitable for continuous reactor operation. Tokamak devices have been built with superconducting magnets since the 1970s and two new devices started operation very recently in China and South Korea. The technology is mature to be used in ITER, but the size, the high magnetic field and the associated mechanical load imposes some problems which need careful design.

Prototypes of some ITER coils have been built and tested, but some development is still needed to increase the operational margin.

3.3. Heating, fuelling, current drive

In tokamak devices the current circulating in the plasma provides sufficient heating power to reach keV temperatures. To provide the 10 keV temperature for reactor conditions, additional heating has to be applied. Such techniques using particle beams and different radio-frequency waves were already developed in the 1980s and are routinely applied in today's devices. In ITER and DEMO the fusion power will be well above the external heating power. As described earlier, 20% of the energy released in the DT reaction is carried by the α particle (^{4}He nucleus), which is a charged particle, thus confined by the magnetic field. It is expected, that in ITER and DEMO alpha particles will provide most of the plasma heating.

Fusion plasmas can be fuelled by simple gas inlet, but the gas is ionized at the very edge of the plasma and the core can be fuelled only by diffusion. An alternative technique is to freeze Deuterium (or later Deuterium-Tritium mixture) and compress the resulting "snow" into a Deuterium ice pellet. This can be accelerated by various techniques to 0.1-1 km/s velocity and injected into the plasma. During penetration into the plasma these pellets shield themselves by a gas blanket (Leidenfrost effect) and thus they are capable of reaching deeper layers of the plasma. Pellet injection is a well developed technique, injection up to 100 Hz during several seconds is routinely applied on modern tokamaks.

The plasma current in tokamak devices is a necessary component of the magnetic configuration. For about 100-1000 s this current can be driven inductively using the central solenoid but for continuous operation additional techniques are needed. Some of the heating techniques are also suitable and tested for current drive. It is an exceptional feature that the pressure gradient in the plasma across the magnetic surfaces can automatically drive plasma current. There is now sufficient experimental evidence, that this so called bootstrap current exists, and it can provide up to 50% of the plasma current in future devices. Only the rest should be driven by heating particle beams and microwaves.

3.4. Plasma-wall interaction

As stated above, a fusion device must operate at much lower particle densities than found under normal atmospheric conditions. This requires a clean vacuum system capable of producing base pressures below 10^{-6} torr. Additionally, the plasma-wall interaction must be carefully designed to avoid impurities in the Hydrogen isotope plasma.

In today's fusion devices a special instrument, called a divertor, is used for controlling the plasma-wall interaction and particle exhaust. Magnetic field lines from the edge of the plasma are diverted into this region by additional magnetic coils. The closed geometry and the high power handling capacity of the plasma facing components (typically Carbon-Fiber Composites, CFC) prevent melting and impurity reflux into the plasma. Experiments showed that the particle exhaust capability of a well-designed divertor is sufficient for removing the expected Helium produced in a fusion reactor. Unfortunately it became clear that CFC is an unsuitable material for ITER and DEMO as Carbon has an unexpectedly high chemical sputtering yield in the low temperature edge Hydrogen plasma. The resulting Carbon and Hydrocarbon molecules are transported in the edge plasma and deposited in certain regions. Hydrogen isotopes, including radioactive Tritium, are buried in these layers and later often break off as small dust particles (Philipps 2003). This Tritium contaminated Carbon dust would increase the radioactivity of the device above allowed levels.

To overcome this problem a development program has been started on two major tokamak devices to test Tungsten as a divertor material. For less demanding regions both Tungsten and Beryllium are being tested. First results are encouraging but a final answer will be obtained only in ITER, where a combination of Beryllium, Tungsten and optionally CFC is foreseen. The power load and the power handling capacity of the divertor is a critical issue for ITER and DEMO.

3.5. Power extraction and tritium breeding

80% of the power from the DT reaction is carried by the neutron. Being chargeless, this particle, after leaving the magnetic field, will be slowed down in the blanket of ITER and DEMO. The blanket will be cooled by either water (in case of ITER) or by He gas (in some DEMO concepts). Electric power will be generated using conventional power generation schemes. Blanket modules will be installed inside the vacuum chamber of the device, so as to protect the vacuum vessel and superconducting coils from neutron damage and power input.

The same blanket modules must also be used for Tritium production in a fusion power plant. In today's tokamaks the fusion reactions are scarce and tritium breeding technologies cannot be tested. It is one of the aims of ITER to develop and test various tritium breeder concepts without providing all the tritium for its operation. Several concepts exist for this purpose, but a liquid Lithium-Lead based and a Beryllium-Lithium ceramics system are the best explored. According to calculations, both concepts can provide the necessary Tritium for DEMO but technical issues like Helium gas cooling, corrosion, material properties must be carefully checked in ITER.

The output of all pumping stations of a fusion reactor must be connected to a tritium plant, where isotopic separation techniques will be used to extract tritium. Such techniques have been developed, and will be extensively tested under operation conditions in ITER. It is worth noting that the particle confinement time in the plasma is much shorter than the tritium fusing rate, therefore tritium will have to be recycled several times.

3.6. Diagnostics and plasma control

Measurements (called diagnostics) on 100 million °C plasmas cannot be made by conventional industrial techniques. Except the very edge, no material probes can be inserted into the plasma, therefore a broad range of new technologies have been developed in the past decades (Hutchinson 2002). These use an extremely wide range of physical processes and incorporate the use of powerful lasers, atomic beams, microwaves, particle detectors but also simple pickup coils and current collector probes. A modern fusion device relies on typically 30-40 diagnostic systems which measure all important parameters of the plasma (density, temperature, magnetic field, etc) with the necessary spatial and temporal resolution. The diagnostic systems are well developed, but the high neutron dose and plasma load on plasma facing diagnostic components will be a challenge for ITER.

A special collection of diagnostics have been developed to diagnose plasma turbulence, which manifests itself in the fluctuation of density, temperature and other quantities. The measurements are extremely difficult and further development of turbulence diagnostics are necessary.

As up to now, fusion devices are typically operated in 5-10 s long pulses (shots), and control is done by trying to force preset time evolution for certain parameters, collect as much data as possible and evaluate them offline. The amount of data from one discharge rose into the Gbyte range but still can be handled. With the new generation of devices reaching 1000 s pulse lengths this approach will have to be changed. Pulses will be cut into segments and control systems will have decision making algorithms. The strategy of researchers to collect all data will also have to change as the amount of data from one experiment will jump into the several Tbyte range.

3.7. Structural materials

Neutron damage of structural materials is expected to be one of the major problems in fusion power plants. In a fission power plant the neutrons are slowed down in the coolant and/or the moderator before reaching the reactor vessel. In a fusion reactor this is not possible. Due to the low plasma density the full flux of 14 MeV fusion neutrons will reach the vessel wall. In one collision with an atom in the structural material the neutron transfers much more energy than the binding energy of the atom in the crystal lattice. The fast atom will collide with other atoms and finally a full cascade of displaced atoms is produced.

Additionally to elastic collisions, neutrons also trigger nuclear reactions in the structural materials. Some of the resulting nuclei are radioactive, therefore the structure of the device is activated. Helium nuclei (α particles) are often generated in these reactions, which means that irradiation produces Helium gas inside the materials. The gas forms small bubbles which later fuse to larger ones and produce voids in the materials.

Small material samples are irradiated in the core of fission research reactors and their mechanical properties are tested after irradiation. A special low-activation fusion steel material called EUROFER has been developed and characterized in this way, which is now the first candidate for structural material of the DEMO reactor. For ITER, the irradiation damage is not critical as the fusion power is 5-6 times below the requirement for DEMO and ITER will only be operated in pulses.

The irradiation studies in fission reactors are lengthy and cannot give final answer because neither the spectrum nor the dose is identical to what is expected in DEMO. A special test facility called IFMIF (International Fusion Material Irradiation Facility) should be built in parallel with ITER to test materials up to DEMO irradiation doses. IFMIF will be an accelerator driven device, where high-power deuterium beams will fired onto a flow of liquid Lithium target and produce DEMO relevant dose and neutron energy in a small volume.

Besides irradiation damage, structural materials should also withstand high temperatures in some regions. The critical point is inside the blanket, where the power is taken away by the coolant. The higher the coolant temperature, the better is the overall plant efficiency. EUROFER and other steels have a temperature limit at around 500 °C, therefore high efficiency gas cooled reactors require special materials. Some DEMO concepts suppose that advanced alloys or SiC materials can be used which would boost plant efficiency, reduce costs and also activation.

3.8. Maintenance

Unlike in a fission reactor, fuel in a fusion power plant can be replaced continuously in the form of gas inlet or the injection of frozen DT pellets. This means that fuel supply does not require regular maintenance periods. On the other hand, neutron bombardment will change the properties of the structures close to the plasma, the blanket and the divertor. Although the rate of damage for a fusion power plant is not known exactly, from irradiation tests it is expected that the blanket will have to be replaced every 5 years and the divertor even more often. Components of the device behind the blanket (vacuum vessel, coils, etc.) will last for the whole lifetime of the reactor. Blanket and divertor replacement is a major maintenance process, therefore the layout of the reactor must this take in into account. ITER will not have the neutron dose which requires replacement of its components, but due to activation remote maintenance will be a must in that case as well. For DEMO different remote handling concepts are being devised. In one scheme, the blanket is divided into a large number of smaller (~10 tons) modules which can be handled by a robotic arm system. In another concept larger banana shaped modules are handled as one unit. Here the weight is in the 150 t range and special large access ports have to be designed for the tokamak. In both concepts the divertor would be divided into modules rotated in the bottom region of the design on a rail system. These modules could be removed through some of the lower maintenance ports.

3.9. Complexity and safety of the device

Although not an individual component, the complexity of a fusion reactor as a whole poses a critical problem. Based on the experience with today's experiments, it is clear that plasma operation will depend on the simultaneous operation of a large number of critical subsystems based on completely different physical basis: heating, fuelling, current drive, diagnostics. On the other hand, power generation ceases immediately if a problem arises, as the plasma cools down within a couple of seconds at most. After the plasma discharge stops, the device will be heated only by the radioactive decay of isotopes in the activated structural materials. According to simulations (EFDA 2005) even in case of a complete loss of coolant natural convection will keep the temperature of the structure below the melting point, no meltdown or uncontrolled reaction can occur.

Another safety feature of a fusion power plant is, that at any time only very little tritium fuel can be found in the plasma, well below 1 g. About 1 kg is expected to be present in the blanket and tritium plant. Even in case of a serious accident the simulated release of radioactivity will not require evacuation of the surrounding population.

4. SIMULATION AND MODELING NEEDS

After reading the overview about the fusion power plant components, one could anticipate that modeling and simulation are necessary for practically all of them. Some of these can be fulfilled using industrial models and simulation codes, even industrially proven techniques will increase the system's reliability. However, in many cases the problems are so special that new models and techniques have to be developed. This needs insight into the involved physical phenomena and will benefit very much from a combination of physics and engineering approach.

4.1. Plasma confinement

Due to the complexity of phenomena, the plasma is not described with one model but by specialized codes. Plasma equilibrium is addressed by MHD codes, while the edge plasma (Stangeby 2000) can be described by a combination of MHD and Monte-Carlo (MC) codes. This latter models the processes involving neutral particles which are moving in the plasma as independent atoms. An additional important component of the edge plasma description is an ionization-radiation model describing excitation, radiation ionization and recombination of neutrals, thus coupling the MC and MHD codes. Phenomena occurring at the plasma-wall interaction must also be taken into account as, besides the core plasma, they provide sources and sinks. For cross-field transport neoclassical particle and plasma turbulence simulations would be extremely important in order to understand particle and heat transport across the magnetic surfaces. Neoclassical transport seems to be well understood, but turbulence simulations need strong development. Here several similarities have been identified with fluid turbulence (e.g. energy transfer between scales, nonlinear interactions), self organized and chaotic systems (self organized criticality, bifurcations). A special area is the evaluation of turbulence measurement data, which does not involve physical modeling but often statistical simulation of random phenomena. The fusion community would surely benefit from interaction with other simulation studies.

4.2. Magnets

Superconducting fusion devices are built into a cryostat cooled down to around 5 K. During cooldown the size of structural components changes considerably, therefore the whole structure should be designed and simulated in a way to be able to keep the necessary precision (typically mm) of the magnetic field and allow for movement of components. An associated problem is to design the mechanical construction of the coil system. During operation, and especially during plasma instabilities, huge forces are exerted onto the coils, actually the magnetic field strength is usually limited by the mechanical stability. During fast transients the fast magnetic field change and current dumped from the plasma to the surrounding walls can generate huge forces on plasma-facing tiles and divertor structures. These have to be modeled using combined electromagnetic-mechanical simulations.

4.3. Heating, fuelling, current drive

Special codes already exist to help designing, optimizing and operating heating, current drive and fuelling systems. These models simulate how waves are absorbed in the plasma, how the fast particles are slowed down and how the shielding gas cloud behaves around a pellet. It is expected that with some refinements these, or similar codes will be capable of describing the next generation devices as well.

4.4. Plasma-wall interaction

The influence of the plasma on the solid state walls involves interaction with two plasma particles: electrons and ions. The mean flux of these two should be equilibrated, therefore usually an electrostatic potential drop (sheath) forms in front of the wall to keep faster electrons inside the plasma.

Electrons reaching the surface of the solid material can not kick out any atoms, therefore their effect is mostly thermal heating. On the other hand ions are more massive and have typically 2 orders of magnitude higher energy than the binding energy in the crystal therefore single atoms can be kicked off from the solid state. This is called sputtering and it is the dominating process. Additionally, some incoming ions become attached to the surface, and form layers on it. The behavior of these layers is extremely important, their characteristics depend on the history of the wall as well. As the particles sputtered from the wall also modify properties of the edge plasma, plasma-wall codes should also be coupled to edge plasma codes. Due to the above reasons plasma-wall simulations are extremely difficult. Models should be validated by experiments but even if the elementary processes can be correctly simulated the condition of the wall surface is often not known.

4.5. Power extraction and tritium breeding

Plasma radiation is absorbed at the surface of the blanket of a future reactor while power from neutrons is deposited in the volume of the blanket. This latter can be simulated with standard neutron codes, e.g. MCNP5. The geometry is usually more complicated than in case of a fission reactor, but tools are being developed to be able to transfer engineering models into neutron code input. From the deposited power standard engineering simulation codes can be used to calculate temperatures and heat transfer to the coolant. Steam generators, He gas turbines will be the same as in other power stations therefore models should be applicable.

Tritium breeding is new technology but determination of the amount of generated Tritium can also be done using models developed for fission. The penetration of tritium through breeder materials, its extraction and cleaning process is much less standard, and modeling would need an interdisciplinary approach: chemistry, physics, materials science is involved.

4.6. Diagnostics and plasma control

Diagnostics are an extremely broad field in fusion, with many techniques and physical principles used. This way modeling is also very much dependent on the actual technique in question: optics, microwaves, particle beams, etc, and a large variety of specialized codes exist for different diagnostic systems for current experiments. For future devices it became clear that these have to be complemented by detailed engineering studies on e.g. heat load on components by neutrons, remote handling operations, protection against plasma radiation, etc.

In the past decade data from diagnostic systems are being gradually used as input into plasma control systems. While in the 1980 s only magnetic pickup loops were used to control plasma position and some density diagnostics to control mean plasma density, recently the most advanced devices use on-line processed data from various diagnostics (radiation, temperature, density, magnetic field direction measurement systems) to actively control plasma operation using the heating and current drive systems as actuators. It became possible to actively control plasma instabilities, improved plasma states (so called transport barriers) and other phenomena. As plasma control systems operate on a ms timescale these on-line diagnostic data evaluation systems heavily rely on advanced data evaluation techniques like neural networks, special tomography codes, pattern recognition.

4.7. Structural materials

Up to now the development of structural materials was based largely on an experimental approach. Recently simulations started to reach a level, where they can at least guide practical work. These techniques will be of extreme importance to assess neutron damage in different materials and guide development. Irradiation tests in fission reactors up to a few dpa (displacement per atom) take years, but for characterizing DEMO materials 150 dpa would be needed. This will take even in the planned IFMIF facility a long time, therefore a validated radiation damage code would be extremely useful.

4.8. Maintenance

As noted above fusion reactors will be activated by the neutron flux and therefore all operations will have to be done remotely. The requirements are much more demanding than in a fission power plant as the geometry is more complex and access is difficult (inside a torus), a broad range of different systems will have to be managed, components can be very heavy (up to 10 100 tonnes) and high precision is needed (mm range). Broken components will have to be taken to a hot cell and repaired there. These requirements can be fulfilled only if remote handling requirements are taken into account form the first moment if the design and operations are modeled.

4.9. Complexity and safety of the device

Complexity of a fusion device and the multitude of physical processes inside it will increase the difficulties very much. In such a machine the number of interfaces can be very high and therefore management becomes extremely important. This applies not only to components, but to simulation codes as well. Codes should adhere to certain standards, should use standardized input and output structures and should be interconnectable. The European fusion program has already started a project to develop or upgrade codes to these standards and create an integrated tokamak modeling.

5. CONCLUSIONS

Magnetic confinement fusion research has reached a maturity where industrial scale experiments are needed. The role of engineering will be extremely important in the construction and operation of these devices, and therefore industrial techniques should be used wherever it is possible. There is a broad range of simulation techniques which are needed and can be applied in future fusion experiments: finite element mechanical, thermal and electromagnetic simulations, computational fluid code, advanced data evaluation and control techniques, maintenance simulations.

Additionally to standard industrial simulations there is a range of modeling techniques which are common with fission and are needed for next generation fusion experiments: neutron transport and activation calculations, simulations for high temperature gas cooling, irradiation damage models, environmental impact and safety models.

Additionally to the above there is abroad range of modeling work which is specific to fusion. These need in-depth understanding of fusion devices and plasma physics. Some of these (especially turbulence models) are in the forefront of physics research and will probably not only use results from other fields, but will also have an impact on them.

Modeling and simulation will be a key component for the development and safe operation of next generation fusion devices, therefore the modeling community is encouraged to take part in this promising undertaking.

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