Structural, Mechanical, and Thermal Aspects of INTOR

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1. Introduction

Before the fusion programme can initiate work on the design of a demonstration fusion reactor (DEMO), the data base has to be completed to such an extent that the successful operation of that DEMO can be expected with sufficient probability. The presently available data base does not yet satisfy this request, particularly with respect to fusion technology. INTOR is conceived as the next step in the fusion programme to bridge this gap between the present generation of large fusion devices and DEMO. Its main objective is the demonstration of the principle reactor plasma physics, and, particularly, to serve as a test bed for the development of fusion reactor technology.

In order to achieve these objectives, any INTOR-like device must be capable of producing neutron wall loads of about 1 MW/m^2 and a fluence of about 3 MWa/m^2 within about 10 years. The fluence requirement comes about after careful consideration of the minimum needs of a well balanced R and D programme for fusion reactor technology. 0.2 MWa/m^2 allows the fulfilment of the physics tasks, 0.5 MWa/m^2 are considered sufficient for the development and testing of reactor relevant blanket concepts and 3 MWa/m^2 are considered just sufficient for the calibration of simulation methods for the long-term performance of materials and reactor components.

From these considerations and from the laws of plasma physics, it then follows that the plasma core of INTOR will have to produce about 600 MW thermal power, $4/5$ of which occurring by the generation of 14 MeV fusion neutrons and the other $1/5$ by 3.5 MeV fusion alpha particles. The latter component is simultaneously used to maintain the burning state of the plasma.

Predictability of performance and high availability of the basic machine are necessary prerequisites for a device whose main task is to serve as a test bed. In principle, this provides a conflicting situation since the optimum confinement configuration and proven technologies are not yet at hand. The conflict can be overcome by applying some technologies which very probably will fail to satisfy the economic part of the fusion reactor requirements

but may be feasible for a test bed. In addition, without any significant reduction in the later applicability of the results it is possible to select the Tokamak as plasma confinement concept and to take advantage of the fact that it possesses the largest data base at present. As long as one remains within the field of toroidal magnetic confinement the technology developed with the help of this concept can easily be transferred to other confinement concepts.

2. Structural, Mechanical, and Thermal Problems

All the above constraints determine the structural, mechanical, and thermodynamical requirements imposed on the design. They are different for the basic machine and the test stations. This separation becomes possible since plasma physics requires the existence of the full torus in order to establish the burning plasma core. Its surface is about 350 m^2 . On the other hand, 1 m^2 is sufficient to investigate surface elements (modules) in the relevant neutron environment. This is more than two orders of magnitude in difference. This paper will mainly deal with the basic machine and its components because it is the primary task to develop the technology for this purpose. The technologies required for DEMO as far as they will be tested in test modules will be developed on a longer time scale. An elevation view of the INTOR phase IIA configuration is shown in Fig. 1.

In a Tokamak the plasma current is an essential constituent of the plasma confinement concept. During a pulse this current starts from zero rises to the full burn value and then falls to zero again. Thus, the external magnetic circuit has to consist of more than one component to account for this plasma current scenario. The toroidal magnetic field has to provide by far the largest fraction of the magnetic energy density. The TF coils should therefore be arranged as close as possible to the plasma surface in order to limit the magnetic field volume for cost reasons. The poloidal field, generated by toroidal loop coils, has the task to balance the hoop force of the plasma ring current and to shape the plasma cross-section for optimum stability. For assembly and maintenance reasons these coils cannot be interlinked with the TF coils but have to be arranged outside of them (see Fig. 1). Therefore, their distance from the plasma is large. Moreover, since the multipole components have a rather short decay length, the currents in these coils are considerable. These poloidal fields interact with the currents in the TF coils and lead to a rather large twist on the total system which has to be balanced by a massive support structure. Furthermore, these twist forces occur in a cycling fashion (about $5 \cdot 10^5$ pulses during the INTOR life) and insulators have to be introduced to separate the structure into small enough units in order to avoid excessive eddy currents. Large fractions of the structure have to be kept at cryogenic temperatures. Only feedback saddle loops will be arranged close to the plasma. Designs of the magnetic circuits have to take into account all these operating conditions.

2.2 Plasma composition control and first wall

120 MW of the INTOR fusion power occurs in alpha particles, heats the plasma, and will finally go to the chamber wall by radiation and via a flux of energetic particles. The most unpleasant effect is that these particles lead to intensive sputtering of the wall if their

energy is high enough. In general, this is the case. Not only that the sputtered atoms are impurities for the plasma finally leading to its extinction via excessive radiation, the wall has also to be made thick enough to survive sputtering losses for sufficient time. Thick walls, however, are particularly susceptible to thermal stresses arising from the cycling operation.

Tailoring of the plasma edge conditions is therefore of utmost importance. Conditions for high density, low temperature plasma boundaries are under development in order to keep the energy of the particles arriving at the wall below the sputtering limit. A divertor is included in the INTOR concept for controlling the plasma edge conditions. The chances are high that a wall not excessively thick will survive the full operation time of INTOR. A larger load will occur at the divertor plates. To account for this the divertor elements are introduced in the form of cassettes which allow easy replacement.

A more difficult point is connected with disruptions of the plasma current occurring from time to time. Where they hit they could be powerful enough to melt the surface of the wall and to sweep away the molten material. It is clear that all measures are taken to keep disruptions under control. Particularly sensitive parts will be covered by protective tiles.

2.3 Plasma heating

To ignite the plasma, it has to be heated by an externally applied power of about 50 MW. RF heating is favoured for this purpose since it requires only antennae in the neighbourhood of the plasma and allows installation of the power transmitter at a remote location.

Critical elements are the antennae which need surfaces still highly conducting even after intense irradiation by neutrons and energetic particles. Similar problems occur with windows which separate the transmission lines from the torus vacuum system. Ceramic is used for such windows. It has to resist high RF power flow and has to be impermeable to tritium.

2.4 Tritium Systems

Any INTOR-like system will have to consume considerable amounts of tritium to achieve the required neutron fluence levels. The tritium consumption may reach values of up to 10 kg/a or even more. Such amounts of tritium are not only expensive but might even not be available to the fusion programme. It was therefore found mandatory to equip already the basic machine with a breeding blanket.

This blanket has to satisfy very stringent requirements. It must not reduce the availability of the basic machine and must be compatible with the pulsed operation of INTOR. In this respect tritium permeation is by far the largest problem, followed by the choice of the optimum breeding material. In critical zones, the tritium permeation rate can be reduced by introducing walls at sufficiently low temperature. Such technologies may not be extrapolable to reactor conditions but might be effective enough for solving the INTOR problems. Reactor-relevant technologies can be developed later by using the test capability of INTOR.

As far as the breeding material is concerned, preference is given either to ceramic materials (Li_2 or Li_4SiO_4 , etc.) or to liquid metal ($\text{Li}_{17}\text{Pb}^{83}$). Ceramic materials are insensitive to cycling operation of magnetic fields but require elevated operating temperatures making tritium permeation a problem. Liquid metal breeders work at somewhat lower temperature but their electric conductivity may introduce some problems arising from eddy currents. Final decisions are not yet taken.

2.5 Maintenance

The INTOR maintenance system is illustrated in Fig. 2. It consists of a semi-permeable frame containing all coil systems. Torus sectors are introduced into window modules which, in turn, house the impurity control modules. All welds are arranged such that they are protected against tritium implantation. Only then re-welding can be foreseen without problems.

3. Concluding Remarks

The INTOR concept takes into account all the above boundary conditions. This paper aimed at giving an overview and arguments for the various requirements under which the individual INTOR components have to work. More specialized information will be found in other papers to this conference.

Finally, it should be mentioned that during the last year or two the data base on the achievable plasma beta has been considerably enlarged. Unfortunately, the assumption made (5.6 %) seems to be above the present predictions somewhat less than 4 %. This point will be picked up by the INTOR team and a new strategy be developed. If the present predictions remain where they are, the INTOR objectives could be met also under these conditions if a combination of the following measures were taken: (i) A slight reduction of the part of beta reserved for the impurity concentration, (ii) a reduction of the neutron flux from 1.3 to 1.0 MW/m² and (iii) a slight increase in both plasma elongation and plasma current to achieve a higher beta. These measures, however, require a new optimization of the INTOR concept.

Fig. 1: INTOR universal configuration.

A: TF coil; B: PF coils; C: blanket;
 D: divertor cassette; E: structure;
 F: plug-in module for RF heating;
 G: bell jar.

Fig. 2: INTOR maintenance scheme.