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CHAPTER Ⅵ: IMPURITY CONTROL PHYSICS

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Japanese Contributions
to IAEA INTOR Workshop, Phase IIA
Chapter VI: Impurity Control Physics

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This report corresponds to Chapter VI of Japanese contribution report to IAEA INTOR workshop, Phase IIA. Special emphasis is placed on pumped limiter analysis for comparative studies between limiter and divertor concepts. Pumping characteristics of divertor/limiter and radiation cooling of diverted plasmas by impurities are also intensively studied.

Keywords: INTOR, Impurity Control, Pumped Limiter, Divertor, Helium Pumping.

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INTORフェーズⅡAワークショップ検討報告書
〔第Ⅳ章：不純物制御物理検討〕

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本報告書はIAEA　INTORフェーズⅡAワークショップへの国内検討報告書の第Ⅵ章に相当するものである。フェーズⅡAではポンプリミタとダイバータとの比較検討をするために，ポンプリミタに重点を置いて検討を進めた。ダイバータ／リミタの排気特性，ダイバータでの放射冷却などについての検討も発展させた。

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1. Introduction

Heat and particle removal issue having its origin in a finite confinement time of core plasmas and impurity control issue stemming from inevitable plasma-surface interactions in those situations require well-balanced developments both in plasma physics, particularly peripheral plasmas, and in engineering centred on heat removal plates. Looking back into past fusion researches, the impurity control issue played an important role in production of high temperature plasmas, and in a path to fusion reactors it will hold a essential key to their success. In the INTOR workshop, the impurity control issue has been actively wrestled since the Phase Zero workshop [1], with recognizing it as one of crucial issues in designing a reactor following the upcoming large tokamaks under construction.

In the history of the impurity control studies in tokamaks up to now, emphases have been placed in trying to keep plasmas from impurities as cleanly as possible in order to get higher temperature plasmas. On the other hand, taking into account formidably large heat to be handled in future tokamak reactors, the impurity control meausre has to change its direction toward harmonized co-existence with impurities, where most part of plasmas heating power must be removed through radiation caused by impurities [A5]. Some symptom of such tendency is already observed in the upcoming large tokamaks [2]. The INTOR seems to be just on a corner of the turnaround in the impurity control strategy. The impurity control design in the INTOR, therefore, depends strongly upon which way is enphasized, that is, the thorough suppression of impurities or the positive utilization of them.

In selecting a divertor system in the INTOR Phase One conceptual design [3], which was concluded to be the most reliable impurity control concept, plasma behaviors in a divertor region and correlated pumping characteristics of helium ash were mainly investigated from a plasma physics viewpoint, along with studying engineering problems regarding to the heat and particle removal from the INTOR plasma, including the assembly and maintenance of the divertor system. It was finally concluded that the divertor of the INTOR conceptual design could be workable in controlling impurities.

In the INTOR Phase IIA workshop, the impurity control issue was appointed for the critical issue to have to be developed from the viewpoints of both plasma physics and engineerings. In particular, the special group, consisting of plasma physists and engineers involved in the divertor/limiter and first wall design, was organized.

On reflection of the conceptual design of the Phase One INTOR, the fundamental background of the Phase IIA INTOR workshop is the reduction and optimization of the cost by means of reducing the reactor size and employing economical system [N9]. Along this line, the pumped limiter concept was decided to be studied as the impurity control method from both plasma physics and engineering with continuing the divertor study at the same time, and finally all-over comparisons will be made between the poloidal divertor and the pumped limiter.

In designing the impurity control system, the following items have to be investigated in the physics aspect.

1) Plasma parameters and their behaviors in the scrape-off layer, which is in contact with the limiter/divertor plates.

2) Impurity behaviors in the main and scrape-off plasmas, which are directly related to the heat removal issue.

3) Helium ash exhaust characteristics.

4) Compilation of divertor/limiter experimental data.

All of the above physical items have connection with engineering issues about the divertor/limiter problems, and therefore investigations must be performed with a close connection between physics and engineering.

Alpha heating power in the final-state fusion reactor would reach around 1 GW [4]. The thermal output of the reactor is increased probably in direct proportion to its volume, while the thermal load of heat collector plates is approximately directly proportional to their surface. It means that the larger thermal output causes the more serious heat removal issue. Taking into account more challenging plasma parameters in the future reactor design, e.g. a commercial reactor [4], its plasma size is not byond a factor of two of the INTOR, while the alpha heating power increases by about one order from the INTOR. To cope with such a tremendous large power, which would make engineering problems, such as heat removal and collector erosion, more troblesome, and would cause to increase the impurity level in the plasma, it is indispensable for the tokamak fusion reactors that most part of the heating power has to be transformed into a radiation loss before it reaches heat collector plates, unless the remakably inovative progress will be made in the heat collector technique [A5]. The heat load to be removed through the collector paltes, therefore, would amount to 100-200 MW at least, because almost all of the power, i.e. 99%, could not be radiated stably.

The alpha heating power in the INTOR amounts to byond 100 MW.

Establishing the handling technique of about 100 MW power witout the impurity radiation loss is great benefit for the future reactor design in plasma physics and engineering. Realizing the reduction of the heat load through the impurity radiation, on the other hand, is also a great progress in core plasma physics. The above both ways are indispensable techniques to the tokamak reactors. When the impurity cooling concept would be adopted for the INTOR reference impurity control, the high heat load removal technique might have to be developed in the running R and D program along with the INTOR. In the contrary case with less-impurity, the necessary data for the impurity cooling should be compiled in the upcoming large tokamaks and the supplementary tokamaks running with the INTOR. Which way should be employed for the IMTOR is an open question from the viewpoint of the impurity control strategy, and it requries all-over studies on impurity control [A5].

The heat load on the limiter/divertor plates can be controlled through the impurity radiation as mentioned above, which also has great influence on the energy balance in the plasmas, the impurity behavior therefore is significantly important. In the pumped limiter case, the power generated in core plasmas could be radiated by the limiter surface material impurity or impurites injected externally. In the divertor case, the radiation cooling could be potentially realized only in the diverted region without seriously contaminating the main plasmas. The reduction of the heat load on the limiter/divertor plates utilizing the impurities therefore requires the tuned coexistence with impurities, which play an essential role in the plasma energy balance. On the other hand, in the case suppressing impurites, the impurity from the limiter/divertor plates could be partly shielded by means of the shielding effect of the scrape-off plasma and then the impurity behavior in the plasma periphery is also crucial.

For the limiter/divertor design, not only the transferred heat to it, but also those informations such as incident particle species, their incident energy, and their spacial profile are necessary. These parameters hinge on the scrape-off plasma characteristics in front of the limiter/divertor plates, and their structure, size, and materials are therefore strongly dependent on it. The scrape-off plasma parameters, of course, greatly depend on the impurity radiation as above mentioned, and could be also controlled to some extent by gas supply methods, gas-puff and/or pellet injection, and by the recycling neutral particles in the divertor region, which corelated with the pumping characteristics. In particular, the large number of recycling particles in the divertor region is expected to cause the high density divertor operation, which has potential of the low temperature plasmas in front of the divertor plates even without impurities.

The helium concentration in the core plasma, produced through the DT fusion reaction, oughts to be diluted below a certain value, e.g. 5%. Otherwise, the thermal fusion output would decrease, and moreover its large concentration, which causes the higher beta value, might results in the termination of a normal operation of plasmas. Whether or not the helium concentration of the core plasma could be kept under a certain level hinges both on particle confinement time of core plasmas and on performance of a pumping system. If the particle confinement time might approach to 10 s, it would be difficult to keep the helium concentration below the allowable limit, and some countermeasures would be necessary expelling forcedly helium ash out of the core plasmas. The present expectation is a few seconds in the particle confinement time, and the argument on it is not further extended here. The pumping performance, which can mainly adjust the helium concentration, is governed by both the pumping system consisting of pumping ducts and pumps, and the helium behavior near an entrance of the pumping ducts. In designing the evacuation system and probably the tritium system, the investigations on neutral gas behavior is unavoidable and should be developed as one of critical issues.

For the limiter/divertor design, disruptions are remarkably influencial, which accompany terribley high heat load in a very short time scale and induce disruptively large electromagnetic force on structures of the machine. As mentioned in [N1], the better understanding of the disruptions and the countermeasures for them are now going on, but countermeasures controlling them are too immature, and therefore the limiter/divertor design should include their effects to counter them.

Necessary informations on the disruptions for the design are their heat load distribution on the limiter/divertor and the first wall, and its time scale. Their scenario influences the limiter/divertor design, and could change even the over-all concept of the reactor. The progress in understanding the disruptions are quite slow due to their contingency and short time scale, some progresses however have been made. In the Phase One workshop [3], the plasma energy plus accompanying magnetic energy were assumed to be dissipated on the first wall. Based on the recent progressed understanding, the disruption scenario has been changed (see [N1]), in which the considerable part of the plasma energy comes on the limiter/divertor surfaces whether they are on the inboard or outbord and the more severe time scale is also added as an option. Those changes are a big burden for the limiter/divertor design, meanwhile they can ease the first wall problem more or less.

Reviewing experimental data regarding the impurity control and reflecting them to the design lessen uncertainties in the design and make it more realistic. Experiments on the impurity control by means of the limiter or divertor make a steady progress. In particular, the helium ash exhaust by the limiter/divertor has had its confidence judging from the recent results. Especially, the possible high density divertor operation could ease the pumping requirement and make it more realistic [5].

Stimulated with those experimental successes, the computational studies on the scrape-off plasma reaching the limiter/divertor plates has also made a remarkable progress. They can explain the experiments well to some extent, and moreover contribute to the limiter/divertor design in the INTOR [6].

2. Pumped Limiter

In the INTOR Phase One workshop, the divertor concept was chosen as a reference impurity control system, and studies on behaviors of diverted scrape-off plasmas and on related technical items were developed, and it was finally concluded that the conceptual divertor design could be workable and compatible in the INTOR machine [3]. In those studies, te following issues were found to need further investigations.

1) The more detailed analyses on divertor plasmas and their experimental researches.
2) The effectiveness of an open divertor configuration, featured by short and wide throat of the divertor.
3) The impurity shielding performance, in particular, the compatibility of the high-Z divertor plate.
4) The tendency toward a large-size, caused by a special space necessary for the divertor.
5) The increased power supply stemming from both the divertor field configuration itself and the larger coil systems due to its large-size above mentioned.

The INTOR Phase IIA workshop was to forcus its effort on critical issues, behind which the cost optimization is hidden by reducing the reactor size, simplifying it, and optimizing power supplies. Responding to those movements, the impurity control issue was resolved to be focussed its study effort mainly on the pumped limiter concept, along with continuing the divertor study.

The pumped limiter, the same concept as a conventional limiter used in tokamaks, is one modified so as to be able to evacuate a part of particles flowing into the limiter. Actually, particles in a outer scrape-off layer are guided into the backside of the limiter and are partly pumped out through pumping ducts equipped near the neutralizer plates. The pumped limiter, basically same as the simple limiter, has no ability to control impurities, which is the major drawback of its concept. The only expected passive impurity shielding mechanism is the shielding effect of the scrape-off layer plasma streching to the limiter surface.

The expected beneficial advantage of the pumped limiter is the potential reduction in the reactor size and its power supply [N7∿N9], which coincides with the fundamental policy of the INTOR Phase IIA workshop. In the pumped limiter magnetic configuration, it is unnecessary to divert the scrape-off layer away from the plasma surface, and the limiter is so placed as to intercept closed magnetic surfaces of a scrape-off layer, which could reduce the volume of the vacuum chamber. Adjusting properly the limiter position, the space occupying by the divertor could be saved considerably. In comparison with the divertor requiring the relatively large poloidal power supply due to the proximity of the magnetic null-point to the plasma surface, the pumped limiter needs the less power supply partly because of remoteness of the null-point from the plasma. The reduced size above mentioned, furthermore, could ease the power supply requirement (see [N9]).

The necessary experimental researches related to the pumped limiter are followings.

1) Performance of helium ash exhaust.
2) Controlability of impurities.
3) Removability of high heat load.

No experimental test has not yet been performed on actual evacuation of particles by the pumped limiter. However, the experimental results using the modified limiter, placed in the scrape-off layer and connected to the external chamber, indicates that particles going into the limiter can travel toward the chamber, the fuel gas pressure of which increases successfully [7]. Taking account of progresses in related computational modeling studies, anxiety about pumping capability seems to be almost removed.

The general tendency of the impurity control in experiments with limiters is that harmful impurity effect is avoided by using low-Z material limiter. The reliable answer to compatibility of the low-Z limiter and applicability of the metal limiter accompanied with expected radiation cooling, hinging on heat load to the limiter, would be obtained after operations of the upcomming large tokamaks.

This section begin with discussing items regarding the position and shape of the pumped limiter, such as a limiter shape mainly depending on its position and thermal load, a thermal load profile, influences caused by changes in plasma position and scrape-off plasma parameters. Representative three conditions of scrape-off plasmas follow, i.e., high, medium and low temperaure scrape-off plasmas. The last is attained by actively utilizing impurites radiating most of plasma heating power. The former two conditions are obtained by adjusting gas supply methods and their quantity.

2.1 Limiter location and shape

2.1.1 Limiter location

Which choice is better for the INTOR, single or double toroidal limiter, is mainly related to the reactor size, and the similar issue about the poloidal divertor was argued in the Phase One workshop [3]. Taking account of the general tendency toward the reduced reactor size in the Phase IIA workshop, the single toroidal limiter was selected due to its saving of space. Regarding the thermal load, there is only a little difference in the single and double limiter, as seen in the divertor case [3]. Engineeringly, the single of course has some benefit in its maintenance for its simplicity.

Three typical locations of the limiter are the bottom, the midplane, and their midway. The bottom location was finally selected considering the following discussions,

1) Sensitivity of heat load onto the limiter to changes in plasma position and shape,
2) Heat load at disruptions,
3) Maintenance including exchanges,
4) Influence on tritium breeding ratio,
5) Pumping system particularly the pumping duct conductance,
6) Vacuum chamber size,
7) Exchangeability from pumped limiter to divertor concept,
8) Compatibility with other systems such as heating system,
9) Required setting accuracy,
10) Compatibility with the shell-structure indispensable for controlling fast plasma movement,

Sensitivity of the limiter location regarding heat load on it to changes in the plasma position is considered. The time scale of the plasma motion could be expected to be more than 50 ms, which is the time constant of the shell-structure holding the core plasmas. The limiter therefore would not come in direct contact with hot plasmas during plasma movement, because relaxation parallel to the magnetic field is much faster than movement. It means that the plasma shift corresponds to changes in magnetic surfaces of main plasma boundary, which result in changes in the thermal load on the limiter surface. The most influencial movements of the plasma therefore are the horizontal shift for the bottom limiter and the vertical shift for the midplane one. The sensitivity of the heat load on the limiter surface is analyzed in [A1] and [A3], in particular serious on the limiter tips. Regarding that item, there seems to be no significant difference between the bottom and midplane limiter location.

Difference in heat load at disruptions is the next item. In the Phase One workshop, the direct heat deposit is assumed to occur on the inboard side and only the radiation heat on the outboard and no direct heat into the divertor except for radiation. The disruption scenario was reconsidered in this workshop [N1], taking recent experimental results into account. It says that a considerable part of energy of the plasma and its accompanying magnetic field is shared with the limiter/divertor, regardless of their locations. Therefore, regaridng the heat load at disruptions, no difference is observed between the bottom and midplane limiters this time. This way, from the plasma physics viewpoint, there is no preference between the two locations.

Followings are the comparisons from the technical points. The maintenance and replacement of the limiter have considerable influence on the location choice, since fairly frequent replacement of the limiter, e.g. once a year, has to be prepared for. Around the midplane various systems, such as a heating system, could be placed, the limiter renewal work at the midplane would be more complex than at the bottom, where interaction with the replacement work could be avoided to some extent. The easier renewal of the limiter is expected in the bottom limiter (see Chapter XI[N9]).

The effect of the limiter location on the tritium breeing efficiency is essential for the INTOR-class machine. Its rough comparison among the above three locations is in the next chapter (see Chapter VII [N5]). The conclusion is that there is no significant difference.

The evacuation system, particularly the pumping duct, which could interact with other structures, should be discussed in connection with its location. The pumping duct from the midplane limiter to vacuum pumps, which could be placed on or under the ground (Capter XI[N9]), might be a nuissance. The pumping conductance moreover could be decreased in the midplane case due to its long pumping duct. Superiority of the bottom can be seen in the point.

Some difference emerges in the vacuum chamber volume, resulting in the reactor size. The space for the bototm would become relatively larger than for the midplane, which would occupy no substancial space, when the structure for the replacement is well utilized. Furthermore, in the bottom case, up-down symmetry is broken, and it could have some worse effects on supporting structure and so on. The up-down symmetry would make various analyses simple. The midplane limiter is much superior to the bottom on the vacuum chamber size and the symmetry of the device.

Space around the midplane, which is used for other important devices such as heating systems and test modules, is precious. Occupying such a Valuable midplane space with the limiter is not so preferable. In particular, the limiter with its width of about 2 m is toroidally continuous structure, and its influence on other structures is fairly serious.

Exchangability between the limiter and the divertor is an interesting viewpoint. At this workshop, the divertor could be synthetically superior to the limiter. In future, however, the limiter has its potentiality of assuming greater prominence. The easy change from the divertor to the limiter concept is preferable, i.e. the bottom location is suitable.

The compatibility with the passive shell-structure, which is indispensable for the plasma positional stabilization, is crucial in selecting the limiter location. The passive shell-structure is expected to be placed close to the plasma in the outboard blanket and to be modified into the multi-divided structures [N2] and [N8], and it could seriously interact with the limiter on the midplane.

The required accuracy for setting the limiter is also an intriguing point. In high beta plasmas at the INTOR ignition point, gap between magnetic surfaces widens by a few times from the midplane to the bottom. It means that the midplane limiter requries much exactness in setting it than the bottom.

Summarizing the above discussions, there is no preference between the bottom and the midplane for the physics items, but much superiocity is observed in the bottom from the engineering viewpoints. The midway location between the bottom and the midplane is seldom touched on. The midway limiter can avoid the large drawback of the bottom, i.e. the tendency of increased vacuum chamber volume, keeping the most advantages of both the bottom and midplane. But the midway location can not escape from the interaction with the passive shell-structure. Judging from the above discussion, the bottom location was lastly selected for the pumped limiter.

2.1.2 Limiter shape

The heat load analyses on a flat-type limiter can be seen in [A1]. The most serious difficulty is the maximum heat load reacing 4 MW/m^2, since the maximum removable heat load might be under $\sim$2 MW/m^2, even taking account of the development in future. The shape limiter can resolve the difficulty, and the typical results are shown in [A3].

The issue of the heat load of the pumped limiter is related to pumping issue, discussed later. On the limiter chip, the heat flow of its poloidal direction happens to be normal to its surface. In principle, the heat load can be reduced as small as possible, but in that way the location of the limiter chip is far away from the main plasma surface and the pumping requriement can not been met eventually. The minimum heat load at the limiter chip is determined from the pumping characteristics, i.e. a need on how many particles should be guided into the backside of the limiter, which, of course, strongly depends on the scrape-off parameters, particulary temperature and density decay length.

The choice on the single or double blade limiters is not so difficult, while the single blade limiter could reduce its occupied space. Given the pumping speed, the limiter chips of the double blade can be further away from the main plasma than of the single. The fact can ease the heat load difficulty on the limiter chips, which is serious as can be seen in the above. The double blade-type limiter is selected from such considerations.

The thickness of the limiter chip should be paid careful attention in its design. In the engineering aspects such as erosion by sputtering, cooling system, and supporting structures, the thicker limiter chip would be better. The scrape-off plasma layer, however, is around 10 cm in its thickness, and the maximum width of the chip should be under 5 cm at most. It could be strong restrictions on the supporting and cooling structures and the limiter life.

2.1.3 Power loading

The permissible power flux density on the limiter surface depends on limiter surface material, heat sink material, structure and size of the limiter, bonding method between the surface and heat sink materials, thermal stress, and so on. The details are described in the next engineering studies [N5].

The maximum allowable surface temperature of the limiter is limited partly under the one corresponding to the endurable vapourization pressure of the limiter material. In the case where the sputtering yield increases with the temperature of surface material, e.g. carbon, the restricted surface temperature should be under the one corresponding to the permitted sputtering yield. The temperature inside the limiter is limited by the thermal stress, in particular the most serious at the bonding surface between the surface and heat sink materials. Whether or not the thermal stress standards should be kept is contraversial, because both materials are not structual materials. In this workshop the thermal stress is regarded as just a reference and not the strict limit [N5].

The thinner limiter surface material could reduce its surface temperature. On the other hand, the life time of the thin limiter is short due to the erosion by the sputtering during the normal operation and the evaporation at disruptions. Judging from the actual limiter structure and size and much experience of the limiter design so far (Chapter VII[N5]), the maximum heat load density is concluded to be 2-3 MW/m^2, in which the future technical progress is included.

The above heat load can not be applied directly to the limiter chips, the structure of which is nearly half-cylindrical, and the heat removal becomes more severe than the flat surface. Taking account of the difficulty of cooling structure, the maximum heat load should be reduced to 1-2 MW/m^2 at the limiter chips [N5].

The heat load of course depends on the equilibrium field configuration and the scrape-off plasma parameters. In the limiter design, the limiter shape is calculated to satisfy the given heat load profile on the limiter surface, as shown in [A3].

2.1.4 Variations in power loading due to changes in scrape-off parameters and plasma position

The heat load profile on the limiter surface is sensitive to not only the plasma position, but the scrape-off plasma parameters. Once a operation mode is fixed, the latter is not expected to change so widely in normal INTOR operation. The scrape-off plasma parameters could be estimated to some extend from results of the upcoming large tokamaks, the uncertainties of them, however, can not be removed completely because of the difference in the plasma heating power. The variations in the heat loading on the limiter surface can be seen in [A3], and it can be found that the influence of the changes of the scrape-off plasma parameters is not so permissible. Some modifications of the limiter design would be unavoidable before the INTOR normal operation can be fixed.

The plasma column changes inevitably its position, even once the operational mode would be fixed. The elongated plasma is intrinsically unstable against the vertical positional disturbance, which is, of course, stabilized by the passive shell-structure and the active poloidal coils (Chapter IX[N8]). The vertical perturbed motion induces the currents in the shell-structure and the coils, which also change plasma shape and radial position, and it results in the variation in the heat load distribution of the limiter. Some details are shown in [A1 and A3]. It is concluded that, given the changes of the plasma position in a few cm and of the elongation in ±0.05, it is necessary to prepare for the heat load margin of around, 1 MW/m^2, the time scale of which is about 0.1 s.

2.2 Low radiation, low density condition

For plasmas with low radiation, which means not to utilize intentionally large impurity radiation loss, their scrape-off plasmas are heated by around 100 MW heating power. When a pellet is adopted as a fueling system, which can supply the fuel inside the hot plasma core, the scrape-off plasma density decreases along with the increase in its temperature.

The scrape-off plasma, heated with the input power of around 100 MW, would be forced to has its temperature more than 100 eV, except for the extreme case, e.g. a extremely high density in the scrape-off layer, which is not considered to be realistic. Being in contact with such a scrape-off plasma with more than 100 eV, the sputtering yield of metalic limiter surface materials could be beyond unity, taking the plasma sheath potential and the ionic number of the material into account. The fact prohibits the metal surface limiter, and the candidate limiter surface materials are restricted to low-Z materials.

In regard to erosion of limiter surface materials by sputtering, the higher scrape-off temperature is preferable to the lower temperature, since the sputtering yield is beyond its maximum there and the particle flux is reduced in inverse propotion to its temperature. The scrape-off plasma parameters in this region are investigated in [A3], which also discusses the shape of the limiter and the pumping requirement. The typical scrape-off temperature and density are 700-1000 eV and $1 - 2 \times 10^{19}$ m^{-3} at the surface between the main plasma and the scrape-off layer.

The big concern about the high temperature scrape-off is its realizability. Up to now, such a high temperature scrape-off has not been observed in experiments. Arcing, which is reviewed in the next chapter (Chp.VII[N5]), is the most plausible candidate which impedes discharges (at plasma startup phase) from going into such a high temperature regime.

Another concern in the region is the large pumping requirement, which is caused by the reduced scrape-off density, e.g. typically 5×10^5 ℓ/s in the effective evacuation speed. Even for such a large pumping speed, the heat load on the limiter chips is inevitably beyond 2 MW/m^2.

In conclusion, the adoption of the low density, high temperature scrape-off plasmas surely eases the large erosion by sputtering. The uncertainty in realizing high temperaure scrape-off plasmas, however, is too large for the pumped limiter to be expected in stable operation. At present, the high temperaure region with low impurity radiation is concluded to be behind the medium temperature region, which however encounters difficulty in erosion.

2.3 Low radiation, medium-high density condition

It is evident from the above discussion that the medium scrape-off temperature, e.g. typically 100-200 eV, can be obtained by increasing its density by means of a gas puffing instead of a pellet injection. In those temperature scrape-off plasma, metal impurities impinging the limiter plate has their energy near 1 keV, around which the sputtering yield has its maximum and beyond unity. The candidate limiter materials therefore limited to low-Z materials as well. The typical scrape-off plasma parameters and the necessary conditions for attaining them are described in [A3].

The uncertainties to be worried are the high erosion rate of the limiter surface, which results in the frequent troublesome exchange of the limiter, and the high impurity level in the main plasma, i.e. whether those large amounts of impurities can be prevented from penetrating to the main plasmas and purity of the plasmas can be ketp within the allowable impurity level.

The possible mechanisms, preventing impurities from limiter and wall from penetrating into the main plasma, are shielding effect of the scrape-off plasma and some special countermeausres forcely pushing impurities out of the main plasma, e.g. the impurity reversal by plasma rotation. Some signs of the latter were observed experimentally and were in crude agreement with the theoretical prediction [8]. The uncertainty whether such countermeasures work well in INTOR is, however, still large, and they are too immature to be adopted for the impurity control. There is no concrete potential candidate for the countermeasures.

The impurity shielding effect, the quantitative effect of which is not so decisive, was confirmed experimentally in many device and analized theoretically [9]. In reference[A1], the necessary impurity shielding is studied, instead of investigating whether the plasma purity can be kept under such a high erosion rate condition of the limiter. For instance, in a case of carbon limiter, the necessary shielding efficiency is several tens percents to keep the carbon in the main plasma below a few percents. Whether this requirement for the shielding is attained or not is an open question at present, but its attainability seems to be fairly high judging from the overall data base at present [1].

The erosion rate of the low-Z materials is considerably high, as mentioned above, due to their relatively high sputtering yield and the large amount of the particle flux, e.g. reaching a few cm/year. (see Chp.VII[N5]). In the actual situations, however, most of sputtered materials of the limiter could return back to the limiter itself and redeposit on it, no matter whether the limiter material is shielded by the scrape-off layer or penetrates into the main plasma. The redeposition effect could remarkably ease the high erosion rate and probably reduce it by about one order. The furthre intensive study is needed in future in that point. For the limiter suffering redeposion, the new concern is the uncertainty of its physical properties, such as the sputtering yield and the thermal conduction, which needs the further research as wel (see Chapter VII[N5]).

Regarding the pumping requirement, the medium temperature region has some advantage over the high temperaure, because of its increased scrape-off plasma density, which moreover could results in the locally relatively high density plasma in front of the neutralizer plate. The necessary effective pumping speed at the entrance of the pumping duct could be reduced under 10^5 ℓ/s.

In conclusion, the scrape-off plasma parameters in the medium temperature region could be operated in high reliability from the view point of its temperature and density ranges, the gas supply method, the pumping requirement, and so on. The big uncertainty concerned in the plasma physics is the capability to keep the plasma purity within the limit. Even only the shielding effect of the scrape-off plasma is expected to work well. The fairly concrete answer to it will be obtained from the experiments of the up-coming large tokamaks. On the other hand, the difficulties in the engineering aspect are large, such as the high erosion rate, the redeposition and its effect on the material properties. It is finally concluded that the INTOR design point should be in the more realistic scrape-off plasma, and the medium temperature region is preferable.

2.4 High radiation, medium-high density condition

In high radiation plasmas, most of plasma heating power is transferred to impurity radiation loss before it reaches the limiter plates. It reduces the scrape-off temperature, and eases the engineering problems of the pumped limiter. If the limiter surface material could be used as a cooling impurity element, the low scrape-off temperature could be stably obtained by taking advantage of the strong dependence of the sputtering of limiter material on temperature, because its operation point lie near the temperature corresponding to that the sputtering yield crosses unity.

As already mentioned in the introduction, the method using the impurity cooling could be indispensable for the tokamak reactor, which releases a tremendous huge power to the scrape-off layer. The biggest unknown factor in this condition is the impurity behavior, i.e. whether the high temperature plasma can coexist stably with the impurity cooling predominantly the peripheral plasma. The present understanding on the impurity behavior is not so progressed as the theoretical prediction is in agreement with the experimental [10]. The base of the INTOR impurity cooling is thought to be too immature.

The engineering limiter design in the region is not so difficult, since the input power to the limiter is reduced to around 10 MW, and the metal limiter is a plausible candidate. Taking easiness in the engineering and uncertainty in the plasma physics, the adoption of this regime to the INTOR was quitted in this study. But the impurity cooling is crucial for the tokamak impurity control strategy and the sufficient continuous study is needed in future.

3. Single-null poloidal divertor

In the Phase One conceptual design study, the single-null poloidal divertor was chosen as a reference concept of the impurity control, and emphasis was placed on divertor plasma studies [3]. On the basis of those studies the divertor system was designed so as to meet various requirements from plasma physics and engineering.

The feature of the INTOR divertor, compared with conventional divertors, is that it has not a distinguishable divertor chamber and is fairly open to the main plasma, which results from bad capability in shaping magnetic fields by remote poloidal coils placed exterior to toroidal coils. There was some concern about whether such a open-shaped divertor can control impurities from going back to the main plasma. It was finally concluded that the INTOR divertor could operate as a workable impurity control meausre including ash exhaust, judging from both analyses of the divertor plasma using particle model, and encouraging experimental results of Doublet III, the divertor of which was similar to the INTOR [11]. In the Phase IIA INTOR workshop, the main effort is put on the pumped limiter analyses as can be seen in the above discussions, and parallel with it, the divertor physics study is continued to deepen its understanding, especially with enphasis on reduction of the heat load on the neutralizer plate.

In the challenging Doublet-III single-null poloidal divertor experiments, the remarkable encouraging results were obtained on the impurity control [5, 11, 12, 13]. The main results are followings.

1) Metal impurity can be reduced by one order with the divertor operation, which has no special divertor chamber and has an open shape.

2) As the main plasma density increases, the density in the divertor region augment non-linearly along with the reduction of its temperature, probably less than 10 eV.

3) Along with the increment of the density, radiating power also grows up in the divertor region and it consequently abates the heat load on the divertor plate.

4) The neutral particle density in the region near the divertor accumulates by an order of two compared to the non-divertor operation.

5) The intentionally injected helium gas is expelled from the main plasma and is accumulated in the region around the divertor. The fact suggests that the simple extrapolation to the INTOR leads to the realistic small pumping requirement of roughly 10^4 ℓ/s.

Those encouraging experimental results stimulate theoretical studies, and the computational investigation has been developed intensively to analize the experiments and predict the INTOR divertor operation [14, 15].

Among the above exciting results, the following two are crucial for the divertor design.

1) High density divertor operation

For the high density like the INTOR operation, the recycling particles in the divertor region are intensively amplified, and the divertor could be operated with considerably high density. The fact means not only that the resulted lowered temperature lessens the difficulties in the impurity control issue, but that the helium exhaust requirement is significantly decreased.

2) Remote cooling

The high density divertor could help the enhanced radiation due to impurity and/or DT particles in the divertor region. It eases the heat load on the divertor plate and impurity contamination of the main plasma could be avoided.

3.1 Low density scrape-of plasma

Like plasmas with a pumped limiter, the scrape-off plasma density could be adjusted with difference in a gas supply method, i.e. pellet and/or gas puff injections. Low density scrape-off plasmas with a divertor could be obtained by the pellet fuel injection and high pumping performance. The former reduces ionized fuel particles in the scrape-off plasma, and the latter abates recycling particles in the divertor region.

The resutls in reference[A4], which is however not the selfconsistent solution coupled between neutrals and plasmas in the divertor region, indicate that neutral gas density at the pumping duct entrance can not be decreased even with the low density scrape-off plasma (2×10^{18} cm^{-3}) and the high pumping performance (5×10^4 ℓ/s) enough for helium ash exhaust. The fact suggests that the divertor might be operated with a medium density (e.g. a few 10^{19} m^{-3}), which could raise the scrape-off density around the main plasmas. The low density scrape-off layer density is expected to be around 1×10^{19} m^{-3}. As shown in reference[A3], which is not the divertor case, but the pumped limiter, the scrape-off temperature can be estimated near 1 keV.

This time arcing is also the biggest uncertainty concerned in realizing such high temperature scrape-off plasma. The advantages of those high temperaures are the reduction in particle flux to the divertor plate and the sputtering yield because of its decreasing tendency beyond the maximum. It leads to the small erosion rate of the divertor surface.

Another concern is whether such a low density divertor plasma has enough capability in impurity blocking, which is the important role of the divertor. Inadequent progress in modeling study of the divertor leaves it to be an open question. As far as the estimation from the Doublet-III results is concerned, it would be somewhat difficult to control impurities from the divertor plate from penetrating into the main plasma with relatively low density scrape-off plasmas.

The necessary pumping performance for realization of the low density scrape-off is guessed to be less than 1×10^5 ℓ/s (see reference [A4]), which could be much smaller than one for the pumped limiter (several 10^5 ℓ/s) and it could be larger than one for the high density divertor described later. The pumping requirement in this case is not so unrealistic.

In conclusion, the major concerns for the low density scrape-off with a divertor are potential occurrence of arcing and inadequacy in the impurity blocking ability. Those concerns could be removed with the high density divertor operation. Moreover, there might be no merit of considerable reduction of the heat load to the divertor plate by radiation cooling. It is concluded that the low density divertor operation has not so much benefit compared with the medium-high density divertor.

3.2 Medium-high density scrape-off plasma

The medium density scrape-off plasma is most likely for the INTOR. Especially, high density plasmas could be formed in the divertor region and various benefits will also emerged in the technical aspect.

The medium density scrape-off plasma will be produced with a gas puffing and the moderate pumping speed. As seen in reference[A4], neutral particle density near the divertor plate increases beyond 1×10^{20} m^{-3}. In those analyses there is no complete coupling between neutral and plasmas, and the decisive conclusion can not be obtained about the divertor plasma parameters. From those results, however, it can be expected that recycling particles would grow up in the divertor region and the high density, low temperature plasma would appear. How the divertor plasma parameters is going needs analyses with strong coupling between neutral and plasma particles, which will be appear in near future [14].

The Doublet-III divertor results show the high density, low temperature divertor plasmas. It is correlated with impurities, which lost the considerable energy and reduce the plasma temperature. In reference[A2] what amount of impurities is needed to ease the heat load of the INTOR divertor using an appropriate model, which can explain the Doublet-III results. Given an Argon impurity with a reasonable particle confinement time, about 3% Argon impurity can radiate the all input energy into the divertor, i.e. 80 MW, and can unload the divertor plate heat load except for the radiation load.

Major concern is also whether those impurities penetrate into the main plasma and their amount is beyond its permissible level. The Doublet-III high density operation suggests that the divertor impurity blocking works well in metal impurities of the divertor plate and injected helium. Detailed design of the INTOR divertor needs more reliable data base on experiments and future theoretical analyses on them.

4. Pumping

4.1 General studies

A quasi-steady state INTOR operation and control of scrape-off plasma parameters need exhaust for helium ash and fuel particles. As accumulation of the helium ash results in increment of beta value and shrinking in fusion reaction at worst, its concentration to fuel must be restricted, e.g. typically 5% [3]. As described in studies on the divertor/limiter scrape-off plasmas mentioned above, their parameters can be changed by difference in gas supply measures, i.e. pellet and/or gas puffing. Those gas supply measures are an unique controller for the scrape-off plasmas, and they are also dependent upon the evacuation performance at the limiter/divertor region. Those facts charify importance of pumping in the INTOR.

The divertor has its pumping duct close to the divertor neutralizer plate and neutralized particles are evacuated through the pumping duct. The INTOR Phase One workshop concluded the pumping requirement of a few 10^5 ℓ/s including the pumping duct and vacuum pumps after it, based on results from mainly particle modeling studies, which however was immature [3]. For a pumped limiter, particles lying in an outer closed scrape-off layer byond limiter tips are guided to a neutralizer plate on a backside of the limiter and are exhausted through the pumping duct located close to the neutralizer plate. In both cases, the divertor and limiter, the configuration around the neutralizer plate and the entrance of the pumping duct is basically same, and results of typical analysis for neutrals could be applied to both.

Experimental studies related to particle exhaust performance have been reported in recent few years [13]. Experiments with an actual pumping system however has not been observed yet. Most of reports so far discussed possibility of particle exhaust, based on the results of particle pressure in a chamber provided instead of the pumping system.

Interesting results are from Doublet-III divertor experiments similar to the INTOR single-null poloidal divertor [13]. Major results are as follows.

1) Even without a special divertor chamber, (the INTOR divertor is also open-type and unconventional) neutral fuel gas pressure near the divertor region is enhanced by nearly two order compared with the limiter operation.
2) The neutral fuel gas pressure grows up nonlinearly with the main plasma density.
3) Helium gas injection experiments also indicates that helium gas pressure near the divertor region behaves like the fuel as described in the above two items.
4) Compression ratios of the fuel and helium gas are nearly same within experimental error bars.

Those results are highly encouraging for the pumping issue, which indicate the plasible capability of the particle removal by means of the divertor, and suggest furthermore reduction of the pumping requirement.

The pumping mechanism of the pumped limiter is principally same as the divertor. Some experiments, in which a pseudo-pumped limiter with a vacuum duct and a chamber at the end, is immersed in the scrape-off layer formed by the main limiter, indicate that the neutral fuel gas pressure is observed to build up in the chamber [7]. The fact also is considered to demonstrate the pumping capability of the pumped limiter.

The increment in the neutral gas pressure near the neutralizer plate is interpretted to be caused by the multiplication of recycling particle near the neutralizer plate without goging back to the main plasma region. The fact is a great advantage both in easing in the pumping requirement and in reducing plasma temperature in front of the plate.

Those stimulating experimental results promote theoretical analyses on particle removability, particularly those a few years remarkably great progress is made in the divertor modeling [6, 14, 15, 16]. The output from the modeling come to be reflected on the INTOR divertor/limiter design.

Major feature of the divertor/limiter exhaust characteristics, different from conventional ones, is that most of particles neutralized at the plate are reemitted with fairly high energy, i.e. what effects thoes hot particles give on the pumping design. Reference[A4] answers just that question.

The effective conductance of the pumping system after the entrance of the pumping duct is decided from probability on whether particles plunging into the pumping duct can be evacuated or not, and the conductance of the duct entrance. The former, i.e. the pumping probability, as shown in reference[A4] does not depend on the temperature of particles, but strongly depend on the state of duct wall, i.e. on which direction particles are reflected to on collisions at wall. Given the structure and size of the pumping duct and the law of particle reflection, consequenctly, the pumping probability is fixed.

The latter, the conductance of the duct entrance, on the other hand, suffers temperature effect as a matter of course. The analysis in reference[A4] presents that the conductance of the duct entrance is nearly given by particles with average temperature over the pumping duct. Therefore, the short duct, e.g. several tens centimeters, has evidently temprature effect because of weak cooling of particles. In a case of more than 2-3 m in duct length, particles flying into the duct with high temperatures lost their energy at collisions on wall, and the average particle temperature eventually approahces the wall temperature and the temperature effect on the conductance is fading away. The INTOR design probably has its pumping duct length of more than 2-3 m. The temperature effect of high energy particles on the conductance can be neglected.

Reference[A4] also studies the requirement of the pumping system, changing plasma parameters in the scrape-off layer. The features are that the extreme increment of neutral particle density at the duct entrance can be observed with increasing the scrape-off plasma density, and that such phenomena do not depend on plasma temperatures over 30 eV. The fact results in reduction of the pumping speed. Based on the results of reference[A4] which are not complete selfconsistent analyses between neutrals and plasmas and do not lead to a decisive conclusion, the necessary effective pumping speed can be drastically reduced to a few kℓ/s.

4.2 Limiter pumping

The pumping requriement for the pumped limiter is more demanding than the divertor. It results from the fact that only a part of particles in the scrape-off layer is introduced to the backside of the limiter for evacuation.

As shown in the pumped limiter studies (see Section 2), at the limiter tips its contour necessarily intersects normal to poloidal field and its special shape, i.e. semi-cylinder shape, makes the heat removal performance relatively ineffective. Those facts force the limiter chips to be far away from the plasma surface to reduce heat load on it, and results in reduction in particles guided to region for pumping. Furthremore, the decaying density profile in the scrape-off layer enhances the reduction of pumping particles. The decrease in the plasma density in the limiter backside region could also lessen the benefit of the large neutral density at the duct entrance, leading to the large pumping speed.

In the design of the pumped limiter, the limiter shape and its size are determined from an equilibrium magnetic configuration for high beta plasmas and plasma parameters for the scrape-off layer so as to meeting the allowable thermal load on it. That way, the plasma parameters going into the backside of the limiter come to be fixed. The necessary pumping speed, enough to evacuate helium ash at a same rate as its birth rate, can be obtained by coupling neutral particles with plasmas as shown in reference[A4]. Based on the results, which are not completely selfconsistent analysis, the necessary effective puping speed, including the pumping duct and the downstream after it, would be in an order of 10^5 ℓ/s.

4.3 Divertor pumping

In the INTOR Phase One workshop, it was concluded that the single-null poloidal divertor would requrie its effective pumping speed of $(1 - 5) \times 10^5$ ℓ/s [3]. That pumping requriement may be interpretted to be fairly conservative, taking account of its sparse data base and less-developed modeling studies on it.

In contrast to the pumped limiter, almost all of particles in the scrape-off layer can be guided to the divertor chamber and are neutralized on the divertor plate. Moreover, the plasma density in the divertor region is larger than for the limiter case. As shown in reference [A4], these situations increase the number of recycling particles in the divertor region, and could raise the plasma density, and would optimistically lower its temperature. It suggests to ease the pumping requirement.

The results of the high density scrape-off plasma in reference [A4] indicate taht the pumping system with its conductance of a few kℓ/s is enough to evacuate the helium ash with its production rate for the INTOR. Those results, which do not stem from the complete coupling between neutral particles and plasmas, can not be adopted in the INTOR pumping specification for its immatureness, but they strongly insist the reduction of the pumping speed.

5. Supporting studies

No special contributions to this subsection.

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No special contributions to this subsection.

6. Conclusions and recommendations

Along the main line of the INTOR Phase IIA workshop, the pumped limiter concept was added as the impurity control method in addition to the single-null poloidal divertor. Major efforts were put on the pumped limiter study, and the divertor research, the reference impurity control method of the INTOR Phase One conceptual design, was continued to obtain beter understanding.

According to the temperature of the scrape-off layer being in contact with the limiter, the scrape-off plasma conditions can be classified into three typical regimes. From the standpoint of plasma physics, studies in this chapter are concentrated on which conditions are necessary for realization of the above three regimes, and what are the most plausible scrape-off plasma parameters. In the next chapter, moreover, are discussed limiter materials suitable to the each regimes, limiter structures, limiter temperature and thermal stress, electromagnetic forces, erosion by sputtering and disruptions, and its life time.

Advantages of the pumped limiter operation with the high temperature scrape-off layer (700-1000 eV), in which only low Z materials are allowed for limiter surface, are relatively small erosion rate by sputtering in comparison with the middle temperature range. Major uncertainties to be concerned are increment in the pumping requirement due to the low density scrape-off layer, reduction in the impurity shielding effect of the scrape-off plasma, and troublesome arcing. Experimentally, there is no observation on such high temperature plasmas. On the basis of those considerations, it is concluded that the high temperature scrape-off operation is extremely difficult to be stably attined.

The fairly low temperature scrape-off layer (10-30 eV) could be obtained with positive utilization of impurities. Its major merits are extreme reduction in the heat load on the pumped limiter and possibility in stable autmatic control of scrape-off temperature with appropriate choice on limiter materials. That peaceful coexistence with impurities would be indispensable measures for the future tokamak reactors. Concerns in the low temperature regime are just the reliability of the desirable coexistence. Uncertainties of the related data base are so large, that second thoughts must be had about choosing it as a reference impurity control.

The middle temperature scrape-off layer (100-200 eV) could be likely to be realized in most probable, which is the only major factor in the trade-off among them. Other conditions are very severe for the limiter. For example, the limiter material could be limited to low Z materials from considerations on its self-sputtering yield, and the erosion by sputtering is remarkably serious for its life time.

As for the evacuation performance by the pumped limiter, recent experimental and theoretical results have fostered confidence that particles guided to the back of the limiter can be evacuated, though some uncertainties still remain in its pumping speed requriements, which fortunately have tendency to decrease.

Major concerns for the pumped limiter still lie in the removability of the heat load reaching 100 MW and the accompanied impurity issue.

Properly contoured pumped limiter, e.g. such a way that the heat flux density becomes uniform, can receive its heat load within the allowable level. The engineering studies on the limiter are performed for the typical limiter shape with its heat load of 2-3 MW/m^2 (see Chp.VII[N5]). The heat removability at the limiter chips is strongly connected to the pumping performance, and it is a large factor for the necessary pumping speed.

As for the impurity controlability by the divertor, remarkable progresses in experimental and theoretical studies have been made, and make its position secure as a reference impurity control. the increase in the scrape-off plasma density enhances the recycling particles in the divertor region and makes it possible to operate the divertor with high density and probably low temperature, which could results in reduction of limiter surface sputtering. Moreover, taking account of radiation loss by fuel and impurities, sonsiderable reduction of heat load on the divertor surface could be expected optimistically. The enhanced recycling also eases the pumping requriement as well. That way, the high density divertor operation would be favorable for reducing engineering difficulties.

On the basis of the above conclusions, the followings are recommended for the critical issue of impurity control.

1) The medium temperature operation regime is recommended for the limiter operation.
2) The high density operation regime is recommended for the divertor operation.
3) The divertor is recommended for the INTOR reference impurity control.

7. Research and development

1) Impurity behavior in plasmas

Problem description

Plasma cooling technique with impurity radiation will be indispensable in future tokamak reactors, whether they will choose the divertor or the pumped limiter. For the INTOR, that technique is of great benefit in easing the engineering difficulties as well. Great efforts on the issue are now continued experimentally and theoretically. The impact accompanied with it is large, e.g. the failure in impurity cooling would give a fatal wound to the tokamak fusion development at the worst, and in the successful case the impurity control method for the INTOR could be changed drastically. Studies on the issue is urgent.

R and D program description

The compilations of reliable data on it in the temperature range of the INTOR operation are expected for the operation of the upcoming large tokamaks under construction. The compilation of the basic atomic data on impurities and further experimental and theoretical developments on impurity behaviors are nesessary.

2) High density divertor operation

Problem description

The high density divertor operation could bestow great benefits to the divertor impurity control. The techniques are connected deeply to impurity behaviors in the divertor region and could be applied to future tokamak reactors. The divertor is the most credible impurity control method for the INTOR as of now. Some efforts are now continued experimentally and theoretically on the issue. For the more confident INTOR design, the divertor plasma analyses including impurities are demanding.

R and D programme

Experiments of the high density divertor with high power heating, NBI and/or RF heatings, are necessary to pile up the data. Studies on impurity effects in the divertor and developments on fundamental impurity atomic data along with the modeling of the divertor plasmas should be performed.

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