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Report

MAGNETIC DIVERTORS FOR EXPERIMENTAL TOKAMAKS AND FUSION REACTORS

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MAGNETIC DIVERTORS FOR EXPERIMENTAL TOKAMAKS AND FUSION REACTORS

Notes on a Workshop held at
Culham Laboratory, 10 - 12 April 1978

Edited by P.E. Stott

Culham Laboratory, Abingdon, Oxon, OX14 3DB, UK
(Euratom/UKAEA Fusion Association)

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C O N T E N T S

	Page
Participants	2
Introduction	3
Programme	4
Summary of the Workshop	5
Requirements for a Divertor in a Reactor	9
Magnetic Configurations	19
Review of Divertor Experiments	23
Extrapolation of Divertors to Reactors	30
Physics of Divertors and the Scrape-Off Layer	37
Further Experiments and Diagnostics	59
Summary of Present and Proposed Divertor Experiments	67

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INTRODUCTION

The Workshop was organised with the objective of bringing together participants with experience in the various aspects of divertor physics, machine design and engineering, together with those interested in reactor studies. The main aim was to discuss the effectiveness of divertors for controlling the exhaust and maintaining plasma purity in experimental tokamaks and reactors.

In order to encourage open discussion and active participation, we avoided a conference-style of meeting with formally presented papers. We organised a series of small, parallel working groups each devoted to a particular topic which met for an afternoon. The chairman of each group then gave a brief report in a subsequent plenary session in which there was time for a more generalised discussion.

This approach seemed to work fairly well and stimulated vigourous discussions both in working groups and in plenary sessions. Obviously many topics could only be dealt with briefly in the time available and there were many unanswered questions.

These proceedings contain brief reports prepared by the chairmen of the various working groups, to whom I am grateful for their efforts. Although there was no formal presentation of individual papers, some participants have kindly provided written notes of their contributions to the discussions and these are included where appropriate. It is important to stress that these proceedings are intended primarily for the convenience of participants in the Workshop. Whilst they may be of interest to other persons they should not be regarded as a complete record of the discussions which took place, or as a definitive policy document on magnetic divertors.

7th August 1978 P.E. STOTT

Time	WEDNESDAY 12th APRIL	TUESDAY 11th APRIL	MONDAY 10th ARPIL
09.00	Report and discussion on Working Group D	Report and discussion on Working Group A	Opening Remarks: R. S. PEASE
			Aims of the Workshop : P.E. STOTT
10.00	Group E	Group B	Brief introductory descriptions of divertor tokamaks (DIVA, DITE....
11.00	COFFEE	COFFEE	COFFEE
	Group F	Group C	Cont'd PDX, ASDEX, TEXTOR, T12?
12.00	Open	Preliminary discussion of topics for today's Working Groups	Preliminary discussion of topics for today's Working Groups
13.00 – 14.00	LUNCH	LUNCH	LUNCH
15.00	Summary and Conclusions of the Workshop	Working Group D: Extrapolation of Divertors to Reactors. / Working Group E: Physics of divertor plasmas and the scrape-off layer. / Working Group F: Requirements for further divertor experiments and special diagnostics.	Working Group A: Reactor requirements for impurity control, exhaust and plasma-surface interactions. / Working Group B: Magnetic configurations of divertors / Working Group C: Comparison of results from divertor experiments.
16.00 – 18.00	End of Workshop. Coach leaves for Heathrow Airport.		

SUMMARY OF THE WORKSHOP

G. Emmert
University of Wisconsin, Madison, U.S.A.

The Divertor Workshop was hosted by Culham Laboratory, April 10 - 12, 1978. It was preceded by the 3rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices (1) held the previous week at the same location. There were about 45 - 50 participants (from Europe, U.S.A., Japan) representing a variety of backgrounds: design of experiments (such as PDX, ASDEX, TEXTOR), experimentalists from existing devices (DITE, DIVA, ISX, Pulsator), surface physics and plasma wall interaction, plasma theory, and conceptual reactor design.

The meeting was organized using the workshop format rather than presentation of formal papers. The afternoon sessions on Monday and Tuesday (April 10 and 11) consisted of three parallel working group sessions. The morning sessions on the following days (Tuesday and Wednesday) were plenary sessions, where the working groups from the previous afternoon reported on their discussions. Because of this organization, each participant was a member of two different working groups and also had opportunity to comment on the results from the other working groups. The opening morning session was devoted to invited talks on present (DIVA, DITE) and future divertor experiments (ASDEX, PDX) and the closing session was devoted to a summary of the workshop. This particular format allowed for a healthy and informative interchange between people with different expertise and points of view.

The overviews from the DIVA and DITE experiments were presented by Shimomura and Stott, respectively. It was interesting to note the similarities of their results. In both experiments about 60% of the ohmic heating power and 30 - 35% of the particle loss is transported to the divertor target plate. The divertor changes the power balance of the plasma significantly; the fraction of the total power leaving by radiation is reduced by a factor of 2 - 4 in DIVA and 5 - 8 in DITE. Measurements of the scrape-off layer plasma in both devices indicate that the flow velocity along the field into the divertor chamber is a fraction (0.1 - 0.5) of the ion sound speed and that the cross-field diffusion is of the order of Bohm diffusion. The DITE group reports large scale fluctuations near the separatrix.

Keilhacker reported on the status and plans for ASDEX, a large poloidal divertor experiment under construction at IPP, Garching, Germany. This experiment is expected to be operational in the summer, 1979. It has a double-null poloidal divertor generated by two divertor coil triplets with zero net current. The objectives of the experiments are: 1) control of impurities with the divertor, and 2) investigation of the β-limits of a tokamak with circular and non-circular cross-sections. For the latter objective intense neutral beam heating is required; plans call for 2.5 MW in 1980 and 6 - 8 MW in 1982. The PDX experiment under construction at Princeton, U.S.A. was reported on by Meade. It is similar in size to the ASDEX experiment, but has the possibility of studying a broader variety of divertor configurations (inside D, outside D, and four-null). This experiment is expected to be operational in the fall, 1978. It has similar objectives as the ASDEX device and will also use intense neutral beam heating.

A relatively new divertor concept was presented by participants from IPP, Garching and KFA, Jülich. This is the resonant helical divertor, where an external helical winding ($q = 3$) is used to produce magnetic islands on the $q = 3$ surface. The islands play the role of the scrape-off layer; field lines are terminated on target plates in the vicinity of the vacuum pumping ports. An advantage of this system is that the required current in the helical windings is small ($\sim$ 1% of the plasma current) and the windings need not be close to the plasma.

A second novel concept is the ripple bundle divertor presented by J. Sheffield. This is basically a bundle divertor, but placed rather far into the ripple of the toroidal field in order to reduce the toroidal field at the desired stagnation point location for a given magnetic field at the center of the plasma. A concern with this concept is the field ripple seen by the plasma. It was suggested that if the ripple is localized to the zone where the plasma is cold, then a ripple of the order of 10 - 20% is acceptable. In the center of the plasma such a ripple magnitude would be intolerable.

In the working group, Reactor Requirements of Divertors, the discussion centered on the allowable impurity concentration in reactor plasmas, vacuum pumping and helium removal, control of the plasma boundary by the divertor, the power density on the divertor target plate, and the problems of maintenance. The energy loss due to radiation is the limiting factor for high-Z impurities. Some specific calculations are presented in reference 2. For low-Z impurities the depletion of the fuel density is a more severe effect than radiation. This is because the increased electron density due to the presence of the impurities requires a reduction of the total ion density for a given plasma pressure.

The working party, Magnetic Configurations, prepared a chart comparing the physics and technological characteristics of the poloidal, toroidal, bundle, and resonant helical divertor configurations. Clearly, each configuration has its particular advantages and disadvantages. In the plenary session discussion concerning this group's report, attention was devoted to the question of whether or not the characteristics of high unload efficiency and high shielding efficiency are mutually exclusive, especially for poloidal divertors. It was reported that calculations for PDX, ASDEX, and reactors yield simultaneously a high unload and shielding efficiency under the right circumstances.

The technological characteristics of various divertor configurations was considered further by the working group, Extrapolation of Divertors to Reactors. This group prepared a chart giving a rating of the severity of various technological problems associated with the poloidal, bundle, and resonant helical divertors in a reactor. The toroidal divertor was ruled to be impractical in a reactor because of the large magnetic field perturbation and the impact on the aspect ratio. An interesting conclusion of this group is that bundle divertors with normal copper coils are a viable possibility for reactors if the toroidal field at the stagnation point can be kept below 3 - 3.5 T. This value may be raised with further development of the bundle divertor concept. The resonant helical divertor was considered to be an attractive idea, but with the drawback that the charged particles are neutralized on target plates in the main chamber. They must then be pumped through the blanket and shield as a neutral gas. If the pumping ports are kept sufficiently small to minimize neutron streaming, then the flow conductance is a severe problem. The poloidal and bundle divertors have an advantage here, because they can guide the particles through the blanket and shield as charged particles on field lines.

The question of the power density on the target plates of poloidal divertors in reactors was considered by this group and by the group on reactor requirements. Calculations done by reactor study groups indicate that the power density can be very high, especially the local value since it is non-uniform. Techniques for spreading the power over a broader area would be quite helpful.

The working group, Physics of Divertors and the Scrape-off Layer, presented an overview of the existing theoretical work on the scrape-off layer plasma. Zero-dimensional particle balance equations have been used to study the relative importance of certain divertor characteristics, e.g. unload and shielding efficiencies, on the overall performance. A one-dimensional diffusion equation with the effect of parallel flow to the collectors modelled as an absorption term has been used to give estimates of the unload and shielding efficiencies. The same technique of modelling the parallel flow as an absorption term has been used in multi-fluid transport codes to provide a self-consistent treatment of the interior plasma and the scrape-off layer plasma. The scrape-off layer plasma has also been analyzed from the point of view of two-dimensional neoclassical theory, where the loss-cone is filled by collisions only, and by two-dimensional two-fluid theory. In the latter case, the diffusion is not necessarily ambipolar on open magnetic field lines. The wide range of assumptions in the various theoretical models is indicative of the uncertainties in our understanding of the physics of the scrape-off layer plasmas. Guidance from experimental results is sorely needed.

A need for methods to connect the results of two-dimensional theory to one-dimensional multi-fluid codes was expressed. Also requiring further study is radiation cooling by impurities in the scrape-off zone. This reduces the heat load to the target plates and increases the collisionality of the scrape-off layer plasma, but also can destroy the shielding efficiency if the electron temperature falls below the ionization limit. Some attention was also given to the possibility of using secondary electron emission at the target plates to reduce the sheath potential and thereby reduce the likelihood of unipolar arcing.

The experimental aspects of divertors were considered by two groups. The first, Review of Divertor Experiments, reviewed the diagnostic techniques, and their errors, used in the DIVA and DITE experiments and compared their results. The second group, Future Experiments and Diagnostics, developed a list of effects that require further study in present and future devices. Among these are: 1) the effect of the divertor on MHD activity in the confined plasma, 2) the effect of the ripple induced by the bundle divertor on transport in hot, collisionless plasmas, 3) the possibility of using the divertor in combination with various refuelling and heating methods to control the density and temperature profiles, and 4) the development of an empirical scaling law for the impurity confinement time as a function of Z_j, n(r), T(r), etc. An extensive shopping list for the development of diagnostics for the scrape-off layer plasma, plasma-first wall interaction, plasma-divertor plate interaction, and the plasma sheath at the divertor plate was also presented.

In the summary session it was noted that divertor action has been demonstrated at low power density into the divertor chamber. The next step is to demonstrate divertor action at high power density under reactor-like conditions. The upcoming divertor experiments with intense supplementary heating are a significant step in this direction.

References

(1) R. Behrisch, Nuclear Fusion, 18 (1978) 1315.

(2) R.V. Jensen, D.E. Post, J.L. Jassby, "Critical Impurity Concentration for Power Amplification in Beam-Heated Toroidal Fusion Reactors", Princeton Plasma Physics Laboratory Report, PPPL-1350 (1977).

WORKING GROUP A

REQUIREMENTS FOR A DIVERTOR IN A REACTOR

This group was invited to discuss the various functions which a divertor is expected to fulfil in a fusion reactor including reducing impurities, exhausting the plasma and controlling the plasma-wall interactions both within the torus and in the divertor chamber.

Members: M.F.A. Harrison (chairman), P. Harbour (secretary)
R. Behrisch, R. Clausing, S.A. Cohen, H.J. Crawley, G. Emmert,
G. Fuchs, S. Gralnick, T.E. James, G.M. McCracken, J.T.D. Mitchell,
G.M. Miley, D. Meade, K.M. Plummer, V. Thompson, G.L. Varley, M. Söll.

Working Group A: Summary

Reactor requirements for impurity control, exhaust and plasma-surface interactions

Chairman: M F A Harrison
Technical Secretary: P J Harbour

(We do not have an exhaustive list of those present but believe the following to be almost complete, with perhaps three names missing:

Behrisch, Cohen, Crawley, Emmert, Fuchs, Gralnick, Harbour, Harrison, Meade, Miley, Mitchell, McCracken, Peng, Plummer, Varley)

Working Group A considered the reactor requirements on a broad basis. Although many of the problems discussed by the working party and the subsequent plenary meeting are interactive, it is appropriate to summarise them under a series of headings:

1. Is a divertor necessary for a reactor?

One way of avoiding the need for a divertor is to operate the reactor in a pulsed mode with a long particle confinement time, as was suggested in the early Oak Ridge reactor studies. Unfortunately this leads to very short pulse lengths, for example after 10 seconds the plasma could be 10% ash. Even if the pulse length is extended by refuelling and operating right up to the β-limit, the duty cycle of such a system is likely to be poor. The pulse length may be increased by the use of a divertor which will also help to reduce impurities to an acceptable level.

2. Impurity control

The required level of impurity control is conveniently summarised by Jensen, Post and Jassby[1]. In Fig.1, taken from reference (1), the maximum permitted impurity concentration is plotted as a function of the Q-values for a D-T plasma at 10 keV. At Q = 100, corresponding roughly to the ignition situation, the concentration of heavy metal impurities should be kept below 10^{-4} and therefore they should be excluded from the reactor. The concentration of iron must be below 2.5×10^{-3} for ignition at 10 keV and below 7×10^{-4} if ignition at 7 kV is required. Lighter impurities do not contribute significantly to bremsstrahlung radiation so they may be present in larger quantities than the heavy metals. However, they cause Z_{eff} to increase, and they also contribute a large number of electrons to the plasma. If the plasma pressure is limited, these electrons dilute the concentration of the D^+ and T^+ ions and so reduce the reaction rate. Once ignition has occurred Q can be decreased and the permitted impurity level is higher. A beam heated reactor operating near Q = 1 permits very high levels of impurity concentration so a divertor might be unnecessary in this case; however, the resulting cost saving may be less than the extra cost of beam heating. It was deemed sufficient to specify these levels of impurity concentration rather than to try to evaluate various divertors for their efficiency in shielding the plasma by ionisation and removal of atoms coming from the wall or for their exhaust efficiency, which is a measure of the proportion of particles from the main plasma crossing the separatrix which enter the divertor rather than strike the first wall.

3. Distribution of power loading

In reference (2) Conn argued that the unload efficiency of a reactor divertor should be high (ie most of the 880 MW of α-particle power from a 5000 MW(Th) reactor should be transported into the divertor) but this might lead to very high sheath potential at the divertor target and to the possibility of severe erosion by arcing and sputtering[(3)]. The possibility of operating with low unload efficiency and providing an additional thermal shield for the first wall was considered briefly. It is not favoured, since it merely transfers the problems discussed in (2) to the first wall shield. It was recognised that the target neutraliser of an unload divertor was exposed to very high, non-uniform, cyclic heat loads. It is not easy to make the target replaceable, nor to segment the target and make it resistant to arcing. The high heat load problem cannot easily be solved by increasing the target area. Yang noted that under certain assumptions thermal stress can limit the number of thermal cycles to between 10 and 100. The Westinghouse compact poloidal divertor[4] answers some of these questions but by no means all. These non-uniform, cyclic, high heat fluxes were felt to constitute a major technological problem. It was noted that a bundle divertor might offer greater opportunities for increasing the target area and also that a mirror magnetic configuration was superior to a tokamak in this respect.

4. Remote plasma blanket

It was recognised that a cool plasma mantle surrounding a tokamak should be able to reduce exhaust temperature and plasma potential; however, its unload efficiency is inherently low. Another way of cooling the exhaust plasma was discussed by Gralnick and Meade. In this approach the plasma density in the divertor is very high and the degree of ionisation drops to about 30% at the target. Energy is transported to the walls by radiation and charge exchange and to the target by convection. This system requires a high density and low temperature at the separatrix and the unload power must be transported into the divertor by conduction. (The system described is related to that in the PPPL conceptual reactor study[5] but without the high impurity concentration in the reactor plasma.) It is uncertain that such a system can operate without so increasing the density and impurity level in the scrape-off plasma that the α-power is radiated to the first wall.

5. Profile control

A divertor may be used for control of profiles of temperature and density in a reactor. Kadomtsev recognised that a divertor could operate in two extreme modes, shielding or unload, the former requiring a high edge density and low edge temperature while the latter requires the converse. It has now been recognised, for example by experiments on DITE[6], that although these modes are not independent, it is possible to obtain a high shielding and unload efficiency simultaneously. Equally important in the field of profile control are the possibilities (a) to reverse the density gradient and so permit impurities and α-particles to diffuse radially outwards (periodic refuelling and pumping may be required); (b) to control the edge density in order to allow efficient neutral injection; (c) to use profile control as a possible means of controlling the thermonuclear rate and hence the reactor temperature; and (d) to use profile control to prevent undesirable effects from mhd instabilities and to allow much higher β than has been achieved to date.

These applications of a divertor will obviously not be met simultaneously but the combined effects of divertor operation and controlled refuelling and heating will provide the reactor designer with a significant number of control variables.

6. Maintenance

A tokamak reactor or experimental fusion device with a divertor is very complex. Should repairs be necessary to any part of the system the consequences vary from catastrophic to merely severe. Certain parts, eg the neutronics blanket, have inherent life limitations so the system design should minimise their maintenance problems. These components should be replaced or repaired rapidly, safely and economically, such that the availability of the reactor system to the electricity supply company be as high as is economically reasonable. Other parts should never fail in a reactor system and should be designed for extreme reliability, with little or no emphasis on maintainability. No agreement was reached as to whether the toroidal field coils and the vacuum vessel were in this category. However, a reactor divertor system will only be developed through a series of experiments and it was noted that components in the experimental devices will not have been subject to the type of reliability testing which would feature in a commercial reactor. Therefore, all components in experimental devices could be expected to fail sometimes and so maintainability was important. A recent development at Wisconsin, featuring only 8 major TF coils with 8 demountable corrector coils, left much more room for a bundle divertor system than is available with 12 or 16 TF coils so the maintainability of such a system could be considerably improved. It was noted that divertor magnetic elements being inherently difficult to dismantle and reassemble, are designed to be reliable even in today's devices so experience in design for reliability will be rapidly accrued.

7. Recovery of heat

An unload divertor transports up to one-sixth of the total thermal output of a reactor. This quantity of heat must be recovered but it could be at low grade for feedwater heating if divertor design requirements dictate this (eg thermal radiation from the target to cryopump panels must be reasonably low so it might be necessary to maintain a low target temperature). Alternatively, heat recovery could be high grade, limited only by thermal stressing on the target heat exchanger. Direct recovery systems were mentioned but are not viewed favourably if they should prove to be as large as those proposed for mirror reactors.

8. Pumping and recycling

In its simplest form a divertor might be used to exhaust the reactor, separate He from the D & T and recycle the D & T as fuel. A 5000 MW reactor produces 1.56×10^{21} α-particles per second and the number of deuterium or tritium ions which must be pumped depends on the burn-up fraction, f_B. It is $(3.12/f_B) \times 10^{21}$ ions per second. The divertor must be able to pump α-particles and it seems unlikely that gettering pumps will be used exclusively because of their recycling (or memory) attributes and because they are not effective for He. Thus some form of mechanical or diffusion pumping in conjunction with cryopumping will probably be required. Large pump areas are required for low density collisionless exhausts and these areas can only be accommodated with difficulty. However, the Westinghouse compact poloidal divertor may offer a solution to the problem. The alternative high density collisional exhaust should be more easily pumped. However, if the density of such an exhaust is to be high enough to permit energy unload via radiation in the exhaust (see Section 4) then neutrals can recycle into the main reactor plasma. An upper limit to the recycling of neutrals from the divertor is required in order that fast, charge-exchange neutrals should not sputter the first wall too rapidly. McCracken has shown that the wall erosion rate can be as little as 0.05 mm/year for the following conditions: mean sputtering coefficient corresponding to the temperature of charge-exchange atoms is 10^{-2}; reactor volume = 10^{9} cm^{3}; particle confinement time for impurities and protons = 1 second; probability of ionisation of charge-exchange atom as it emerges from the plasma = 0.3; screening efficiency of divertor = 0.9; neutral density in the reactor = 10^{10} cm^{-3}. With these assumptions the recycling of atoms from the divertor must be less than 5×10^{21} atom/second, which is not a very stringent requirement unless the refuelling profile is very flat, in which case there may be no possibility of recycling of atoms from the divertor.

9. Conclusion

Divertors have the potential to solve many problems associated with reactors and their development. It is unlikely that a reactor system will be produced without extensive use of divertors, but divertors have a significant impact on the complexity of a tokamak fusion device. The subjects discussed by Working Group A reflect the concern, which has been expressed to date, for the various problems arising out of the application of divertors. Many problems were discussed briefly or not at all, others more extensively. It was felt that the art of the divertor is young and that many of the problems which seem formidable at present will be resolved as the art develops in the future.

References

(1) JENSEN R V, POST D E and JASSBY D L, Critical impurity concentration for power multiplication in beam-heated toroidal fusion reactors, Princeton Plasma Physics Laboratory report, PPPL-1350, April 1977.

(2) CONN R W, First wall and divertor plate material selection in fusion reactors, presented at the 3rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Culham Laboratory, 3-7 April 1978.

(3) HARBOUR P J and HARRISON M F A, The influence of electron emission at the divertor target of a tokamak fusion reactor, presented at 3rd International Conf. on Plasma Surface Interactions in Controlled Fusion Devices, Culham Laboratory, 3-7 April 1978 (available as Culham Laboratory Preprint CLM-P528).

(4) YANG T-F, LEE A Y and RUCK G W, Westinghouse compact poloidal divertor reference design, WFPS-TME-042, August 1977.

(5) MILLS R G et al., A fusion powerplant, Princeton Plasma Physics Laboratory report, MATT-1050, August 1974.

(6) FIELDING S. J. et. al. Prague Conf. (1977) I, 36.

Plasma properties, submitted for publication in Nuclear Fusion, September 1977. Available as Culham Laboratory Preprint, CLM-P478.

Fig.1 Copy of Fig.3 from Reference (1).

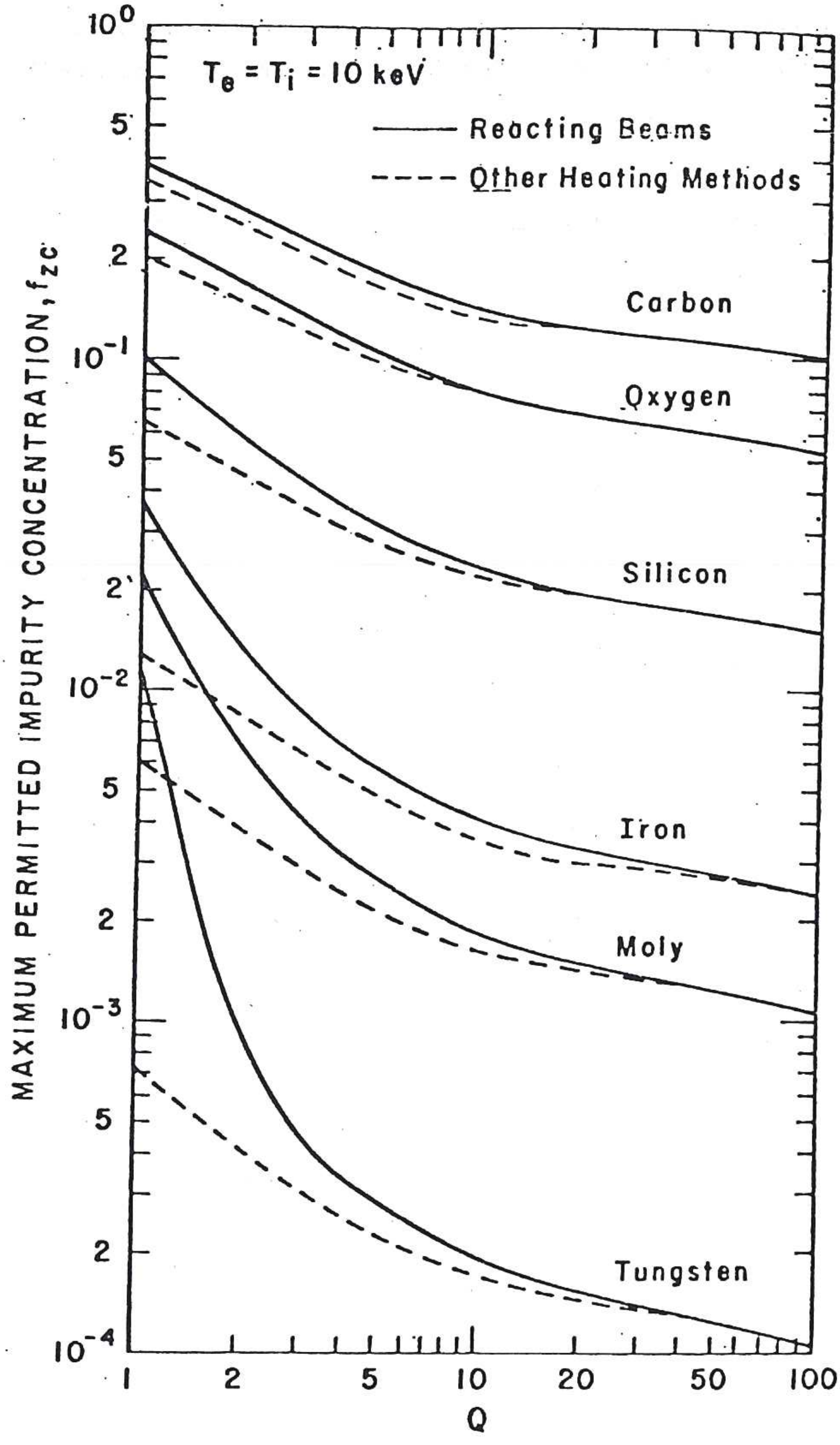

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Fig. 3. Maximum allowed concentrations of various impurity species for attaining given Q-values in a 10-keV D-T plasma. The solid lines are for plasma heating by 200-keV deuterium beams, while the dashed lines are for any heating method other than reacting beams. (Taken from ref [1])

WORKING GROUP B

MAGNETIC CONFIGURATIONS

This group was invited to review the various divertor configurations which have been proposed, to compare their merits and disadvantages and to recommend whether any new configurations should be tested experimentally.

Members: G. Wolf (chairman), K. Lackner (secretary), H. Conrads, F. Karger, M. Keilhacker, M. Okabayashi, A.D. Sanderson, B.C. Sanders, J. Sheffield, W. Spears, P.E. Stott, T. Yang.

WORKING GROUP ON MAGNETIC CONFIGURATIONS

This working group considered briefly a number of different divertor configurations which have been proposed. In the limited time available and influenced by the range of expertise in the Group, we decided to concentrate on a comparison of four particular configurations; poloidal, helical, bundle and toroidal. The Group discussions were conveniently summarised by Dr Karger on the following tables which compare (A) the engineering aspects and (B) the physics aspects of the four configurations. The rating code which was used is as follows:

1	2	3	4	5	X
Easy -	medium -	acceptable -	difficult -	impossible -	not assessed
Zero -	moderate-	acceptable -	strong -	excessive -	not assessed

Where two grades are given (e.g. 1/2), the first number refers to an experimental tokamak and the second to a fusion reactor.

Obviously in the space of four hours we could only make a very superficial assessment of the many problems and on some areas we were limited by lack of direct experience within the members of the Group. For this reason we hesitated to label anything as being impossible, since there may be significant technological developments of which we were unaware. Finally we emphasise most strongly that these comparisons are intended to be only "semi-quantitative" and should be regarded as a working guide rather than a definite comparison.

LSW

A. ENGINEERING ASPECTS

	Poloidal	Bundle	Toroidal	Helical
Assembly/repair (e.g. interlinking coils)	3/4	2/3	2/3	1/X
Neutron Shielding	/3	/4	/3	/2
Forces/Stresses	2/X	.4/X	3/X	1/X
Position of Divertor Coils				
Outside: Blanket Structure	/4	/4	/X	/X
Divertor Chamber	3/3	4/4	4/4	1/1
Not Interlinking B_t- coils	4/4	1/1	1/1	2/X
Limitations				
On: B_t - field strength	3/3	4/4	4/4	1
Pulse Duration (Norm.cond./superc)	2/4	2/3	2/2	1/1
Pumping concepts	2/3	2/2	2/2	3/4
Main Advantage	Symmetry	Not interlocking B_t / Pumping	Unload Efficiency	Low Current
Main Drawback	Interlock B_t-coils	Stresses	Racetrack	Sensitivity / Pumping
Main characteristic	Symmetry	Accessibility	Racetrack	Cheap

B. PHYSICS AND PERFORMANCE ASPECTS

Magnetic field param. near separatrix				
q	$\rightarrow \infty$	$\rightarrow 0$	0	$\rightarrow$ q (a)
$\Delta B/B_{tot}$	$\frac{1}{q.A}$	1	1	$\ll \frac{1}{q^A}$
Length of field line	$\frac{q\pi R}{n}$	$\frac{10\ R}{n}$	πR	$\frac{q(a)}{2[q(a)-\frac{m}{n}]}$
Transfer of field lines				
Outside Blanket	yes	yes	yes	no
Outside TF-Coils	no	yes	yes	no
Diversion towards increased plate surface	3/3	2/2	2/2	4/4
Application as moving magnetic limiter	2/2	2/2	X	4/4

B. PHYSICS AND PERFORMANCE ASPECTS (cont)

	Poloidal	Bundle	Toroidal	Helical
MHD Stability	No experi. without copper shell	no theory	X	no theory
Sensitivity against				
Variation I_p-value	2	2	2	4
Variation Plasma position	2-3	2	2	4
Variation Current Distrib.	3	3	3	2
β_p-increase	2	2	2	3
Effect of Divertor on confinement	1	2-4	4(-5?)	2-3
Main Advantage	Inherent low shielding efficiency Control during start up phase	Inherent low exhaust efficiency lack of symmetry	Field perturbations	Sensitivity Field lines cannot be guided outside vacuum vessel
Characteristic	symmetry	localization	Racetrack	uses resonance

LSW

WORKING GROUP C

REVIEW OF DIVERTOR EXPERIMENTS

This group was invited to review the results of existing divertor experiments, to discuss their similarities and to prepare a summary of the present status of divertor experiments with a recommendation for further work.

Members: A. Mense (chairman), S.J. Fielding (secretary), U. Daybelge, H.A.Classen, E. Ensberg, T. Hsu, G. Haas, H. Niedermeyer, J.W.M. Paul, F. Sand, Y. Shimomura.

REVIEW OF DIVERTOR EXPERIMENTS

Parameters and experimental data from the three present day operating divertor tokamaks DITE, DIVA and T12 are given in the table, compiled by Dr Y. Shimomura, published in J. Nucl. Mat 76/77 (1978) 45 and enclosed as an appendix to this report. In addition to discussing the data presented in the table the working group attempted to assess the accuracy of the experimentally determined parameters.

The first problem looked at was:

Heat flux to collector plates.

DIVA ~ 55% of P_Ω
DITE ~ > 60% of P_Ω.

Measurements:

a) bolometric measurement on collector plates

DIVA ~ est. error ~ 20 - 30%
(Ref. J. Nuc. Sci. & Tech. 17 (1977) 534).

DITE ~ ? not assessed due to need to unfold energy flux from temperature measurement.

b) time resolution

DIVA ~ 0.2 msec for each spatial location
(thin film thermocouple) (JAERI-N7610).

DITE ~ 0.6 msec/line (few μsec/spot)
(Infra-red scanning camera).

c) spatial resolution

DIVA ~ establish toroidal symmetry to 10% using multiple probes - Make thermocouple measurements in orthogonal direction (0.4 mm resolution).

DITE ~ 2-dimensional infra-red camera.
0.25 mm resolution scanning typically 12 cm x 12 cm array across plate.

d) Up-down asymmetry (in e direction) seen in both DITE and DIVA in low density discharges. Can be reduced by higher density operation.

e) From saturation current measurements in divertor zone DIVA finds an epithermal electron flux.

<u>Particle Flux</u> to collector plates

DIVA ~ 35% of $\frac{\bar{n}}{\tau_p}$

DITE ~ 30% " "

measure τ_p:

i) Absolute spectroscopy on H_α gives

$$\frac{N_e}{\tau_p} \simeq \frac{N_i}{\tau_p} \text{ for } Z \sim 1$$

ii) Measure I_{SAT} to all surfaces and use

$$\tau_p = \frac{N_e e}{I_{SAT}}$$

a) DIVA uses uni-directional probe to measure spatial resolution of $\Gamma_\parallel(r)$ (i.e. $I_{SAT}(r)$) can hence determine the plasma flow.

b) DITE measures $n_e(r)$ using omni-directional probe then assumes ion sound speed $v_s \sim \sqrt{T_e/m_i}$, $T_e \sim T_{es} \sim 30$ eV from probe. n_e measurement calibrated against μ-wave in divertor zone.

c) DIVA obtains T_e in scrape-off layer also using electrostatic analyser (½ cm resolution)

0.80 eV from e.s.a.) bench-mark or
100 eV from laser data) calibration check.

d) $v_f \sim 0.3\ C_s$ (DIVA).

<u>Miscellaneous Topics</u>:

Impurity Flow Reversal	-	Possible to test this concept in divertor region as well as in conventional tokamak.
Measurement of neutral density	-	Use Lyman α laser and resonance fluorescence (In development).
M.H.D. turbulence measurements	-	not discussed.
Determination of separatrix	-	DITE - vacuum field: use e^- beam. DIVA - use probes, measuring electron current due to runaway e^-.
X-ray Z_{eff} anomaly factor	-	not discussed.

Resistance Z_{eff} anomaly - not discussed.
factor

Conclusions

1. There is a need to assess the accuracy of impurity flux measurements, as derived from spectroscopic observations.

2. Care must be taken to experimentally resolve errors in measurements.

3. There is a need for the development of new diagnostics to measure scrape-off layer parameters in present-day and higher power experiments.

Impurity

Device	DIVA	DITE	T-12
Radiation loss power P_R/P_{in}	Divertor reduces radiation loss power by a factor of 2 - 4. 30 - 40% (divertor off) 15 - 30% (on)	Divertor reduces radiation loss power by a factor of 5 - 8. 50 - 100% (off), 20 - 30% (on)	
Low-Z impurity	Influx of O and C is reduced by a factor of 2 - 4. Content of O and C is reduced by a factor of 2 - 4.	I_{OII} and I_{CII} are reduced by a factor of 1.5. I_{OV}/n_e and I_{CV}/n_e are reduced by a factor of 2. Content of O is not affected by divertor*.	
High-Z impurity	Intensity of pseudo continuum from gold ions is reduced by a factor of 2 - 4.	I_{MoXXII}: 0.1, I_{FeXVII}: 0.3 Influx of metal is reduced by a factor of 4 - 6.	
Shielding efficiency	50 - 70% for injected C at the farthest point from the divertor. 60 - 80% for injected Al at the farthest point from the divertor. Not large for H.	50% for injected O and C. 80% for Fe. 75% for Mo. 50% for H.	
Impurity back flow from divertor	Small.	Small. Mo concentration reduced by factor of 10 even with Mo target plate	
Remarks	Axisymmetric radiation.	* To maintain the divertor discharge at the same density as the undiverted ones, the gas feed must be increased. This increases the plasma recycling and the influx of O (1977) No quantitative information about symmetry but radiation seems to be fairly uniform around the torus.	No quantitative data on symmetry of spectral lines, but we have no reason to suspect any significant poloidal or toroidal asymmetries.

Main Plasma

Device	DIVA Tokamak Teardrop-like cross-section Axisymmetric divertor	DITE Tokamak Circular cross-section Bundle divertor	T-12 Tokamak D-shape Axisymmetric divertor
Magnetic field B (T)	0.8 - 2.0	0.9	0.8
Major radius R (m)	0.58	1.17	0.36
Minor radius a (m)	0.09	0.19*	0.14 x 0.07
Heating	Ohmic	Ohmic	Ohmic
Heating power P_{in} (kW)	40 - 350	100	
Plasma current I_p (kA)	10 - 50	50	40
Duration τ_j (ms)	20	200 - 600	10
Density n_{eo} (cm^{-3})	$(1.5 - 8) \times 10^{13}$ with and without gas injection	$(0.7 - 1.3) \times 10^{13}$ with and without gas injection	3.0×10^{13}
Electron temperature T_{eo} (eV)	200 - 700 Divertor broadens profile	280 - 320 †	300
Ion temperature T_{io} (eV)	70 - 300 No divertor effect	90 - 100 No divertor effect	
Energy confinement time τ_E (ms)	0.5 - 3 $1.5 \sqrt{q_a}\, \bar{n}_{14}$ (Divertor off) $4.0 \sqrt{q_a}\, \bar{n}_{14}$ (Divertor on)	2.0 - 2.8	
Particle confinement time τ_p (ms)	0.5 - 3 $2.0 \sqrt{q_a}\, \bar{n}_{14}$ (Divertor off) $3.0 \sqrt{q_a}\, \bar{n}_{14}$ (Divertor on)	≈ 30	
Heat diffusion coefficient D_h (cm^2/s)	$(3 - 4) \times 10^3$ No divertor effect		

* magnetic separatrix 0.19
limiter radius 0.26

†The divertor increases T_{eo} from about 200 eV (without divertor a_L=0.26) to ≈330 eV (with divertor, a_L = 0.26 a_s = 0.19). A similar increase is produced by inserting a probe limiter to a_L = 0.19

Scrape-off Layer Plasma

Device	DIVA		DITE		T-12
Electron temperature T_{es} (eV)	15 - 70		25 (from IAEA, 1976, Fig. 13)		10
Ion temperature T_{is} (eV)	20 - 70				
Density n_{es} (cm^{-3})	$(1 - 3) \times 10^{12}$		1×10^{12} (Prague, p.36 Fig. 1)		
Width d (cm)	1		7		0.5 - 1
Flow velocity v_f	$(0.1 - 0.5) \times v_s$, $v_s = \sqrt{T_{es}/M_i}$		$\simeq 0.16\ v_s$		
Diffusion coefficient $D_\perp$	$0.1\ D_B$				Similar to that of main plasma
Heat flux along magnetic field	$q = \gamma T_{es}\ i_s$, $\gamma = 5 - 15$ i_s: ion saturation current		$\gamma \sim 300$		
Power balance		Divertor		Divertor	
Radiation and cx $P_R + P_{cx}$ (kW)	110	40	50 - 100	20 - 30	
Wall P_W (kW)	200	25	50 - 0	20 - 30	
Divertor P_D (kW)		75		60	
Particle balance		Divertor		Divertor	
Wall F_W (s^{-1})	2×10^{21}	1×10^{21}			
Divertor F_D (s^{-1})		1×10^{21}		several tens%	
Remarks	Scaling for T_{es}. Heat flux is consistent with a sheath model. Impurity flux velocity $\approx v_f$.		Ion saturation current onto the divertor target $\approx$ 10 A.		

WORKING GROUP D

EXTRAPOLATION OF DIVERTORS TO REACTORS

This group was invited to consider the problems anticipated in designing a divertor for a conceptual reactor, bearing in mind the requirements identified by Group A and the configurations explored by Group B.

Members: G. Emmert (chairman), H.J. Crawley, S. Gralnick, J.D.T. Mitchell, K.M. Plummer, M. Peng, B.C. Sanders, M. Söll, W. Spears, V. Thompson, G.L. Varley, T. Yang.

Report from Group D

Extrapolation of Divertors to Reactors

The assignment given to Group D was "to consider the problems anticipated in designing a divertor for a conceptual reactor bearing in mind the requirements identified by Group A and the configurations explored by Group B." To some extent technological problems associated with divertors were dealt with in Groups A and B. This Group used their reports as one of the sources of information for the discussion. In order to more sharply define the problem, it was decided to limit the discussion to toroidal reactors (most likely tokamaks) with a power output of the order of 1000 MW_e and operating in a quasi-steady state mode. The typical burn time might be of the order of hundreds of seconds so that alpha particle (and perhaps impurity) removal during the burn is essential.

The methodology used during the workshop was to brainstorm potential problem areas and then give a rating of the severity of these problems for each of the divertor types. The types of divertors discussed were the poloidal, the toroidal, the bundle, and the resonant helical divertor. The rating given to various divertor types for each problem area is as follows:

1 - The solution is state-of-the-art.

2 - The solution is an anticipated extrapolation from the state-of-the-art.

3 - Solution of the problem is difficult, if not impossible, to obtain.

x - The problem is insufficiently assessed.

xx - The problem may be assessed, but the group pleads ignorance.

A word of explanation concerning the "xx" rating is required. There were no workshop participants with first hand experience with the resonant helical divertor. Consequently, the group was hesitant to make a judgement in some areas, but felt that the helical divertor concept was of sufficient interest that it ought to remain under consideration. Rating "3" can be restated in a positive way. Problems given a "3" represent opportunities for creativity and ingenuity; they have the greatest payback in terms of making divertors more compatible with reactor requirements.

After a brief discussion, the toroidal divertor was rejected from further consideration on the basis of being unfeasible for reactors. The basis for this decision is 1) its geometry forces the reactor to operate at such a high aspect ratio that the power density is seriously reduced, and 2) the large field ripple in the center of the device leads to poor confinement of fusion-born alpha particles. Other reasons may also make it unfeasible, but these are sufficient.

The technological problem areas considered are as follows:

1. The forces, and associated stresses, on the coils generating the divertor field and on other coils with which the divertor coils interact.

2. The amount of space available for shielding the coils from the neutron flux. For superconducting coils, the primary limitation is due to radiation damage of the insulators. As a criteria, it was suggested that 80 cm thickness (based on iron and water) is necessary if breeding of tritium is not also required. A different suggestion was 1.0 - 1.25 m of space is required if the space required for headers is considered. For a breeding blanket plus shield a thickness of 1.5 m was proposed. If normal coils are used, the required shielding thickness may be as little as 35 cm.

3. Power consumption using normal coils. Power consumption less than 10% of the electrical output was the adopted criteria. Of course, if there are other components requiring a large amount of power, this value would need to be reduced.

4. Current density in Superconducting Coils. A value of 1000 - 2000 amps/cm^2 including the space for stabilizer, coolant channels, and structural material was proposed as being consistent with what is used in conceptual reactor designs.

5. Power Density on the Target in the Divertor Chamber. It was reported that 100 W/cm^2 is considered standard in boiler technology, fast breeder reactors can have power densities as high as 300 - 500 W/cm^2, beam dumps operate at $\sim$ 1.5 kW/cm^2, and swirl tubes have been operated with a power density as high as 10 kW/cm^2. The latter value however is based on very little experience and is not to be considered for reliable long-life operation.

6. Vacuum pumping requirements including the removal of helium.

7. Unipolar arcs on the target plates in the divertor chamber.

8. Maintenance. The question considered here was: To what extent does the divertor make it harder to disassemble the reactor for maintenance?

9. Utilization of Space. To what extent does the divertor compete with other components for space, either inside the T/F coils or in the central zone of the torus? This is primarily an economic question, since competition for space may require larger T/F coils or a larger aspect ratio.

The results of the workshop session are shown in Table 1. Forces on coils represent a more severe problem for the bundle divertor than for the other types. The severity of the problem is determined by the toroidal field at the point where the stagnation point is to be located and not by the physical size of the device. Scaling to larger size means larger forces, but also more structural material and, consequently, the stress does not change. A value of 3 - 3.5 T at the stagnation point was suggested as being manageable. The problem becomes more severe rapidly as B is increased since the force $\sim B^2$. In the plenary session it was noted that with further development one might find coil configurations for the bundle divertor in which the force for a given field is lower. The ripple bundle divertor concept allows one to have the stagnation point at low field ($\sim$ 3 T) while the field at the magnetic axis is considerably higher. It is not yet clear, however, that the ripple concept will work in a reactor, where the ripple of the T/F coils is not well-localized and the blanket/shield also consume space.

Neutronic shielding appears to be a problem only for a bundle divertor with superconducting coils. The rating of "(1)" for the helical divertor was added in the plenary session.

It is interesting to note that power consumption for normal divertor coils seems to be acceptable in all three cases. The possibility of normal coils is an interesting option that may have other advantages.

The quoted current density limit for superconducting coils is a problem only for the superconducting bundle divertor. This criteria received some criticism in the plenary session as being too conservative. It was reported that the design current density in the Large Project is 2.2 kA/cm^2.

The power density on the particle collector plates is a severe problem in reactor size poloidal divertors. A peak value of 6.7 kW/cm^2 normal to the magnetic field was quoted for the Wisconsin TFTR design. Tilting the plate reduced this by a factor of 10 but the erosion rate due to sputtering is also severe. Estimates based on the average (across the scrape-off layer) power density can be misleading; the power density is sharply peaked because of the fall-off of both the density and electron temperature in the scrape-off layer. This problem does not appear to be conceptually easier in the helical divertor. The bundle divertor has a potential advantage because the plasma is delivered to plates outside the T/F coils. It ought to be easier to expand the area on which the power is deposited, but this has not yet been adequately considered. Hence the rating "2/x".

Vacuum pumping is not a severe problem for the poloidal and bundle divertors in a reactor since the plasma can be guided through the blanket and shield along magnetic field lines and neutralized on a target plate directly in front of the vacuum pumps. The use of cryo-sorption pumps at 4.2° K gives adequate pumping speed for helium as well as deuterium and tritium. The helical divertor is fundamentally different because particles are neutralized on plates inside the main chamber and must be pumped through the blanket and shield as a neutral gas. Flow conductance of these penetrations is the primary problem.

The possibility of unipolar arcs is a potential problem depending on plasma properties in the scrape-off zone. This is primarily a physics question; one cannot say at this time if it is more or less severe with respect to divertor type.

Maintenance of components by remote handling techniques is a severe problem for all fusion reactors using D-T as fuel. Because the bundle divertor does not have interlocking coils, it has a topological advantage over the poloidal divertor. It was noted in the plenary session that this also applies to the helical divertor since the helical field can be generated by finite length straps not interlocking the T/F coils. The rating of "3" in Table 1 is a statement that maintenance is a severe problem regardless of the divertor.

The question of space utilization was not included in Table 1 because the group did not want to give this question same importance as the others. Although the bundle divertor has an advantage because it consumes space on the outside rather than in the crowded interior, it was felt that it is premature to make economics a deciding factor. The more important factors are effectiveness and engineering feasibility.

It was asked in the plenary session if the group felt that the helical divertor concept is of sufficient interest to warrant an experimental test even though its reactor potential may have received some bad ratings. The group chairman (Emmert) responded that he agreed personally with this statement and sensed that the group would also agree with it.

As a caution, it should be noted that these ratings were made in a single session of 4 hours duration. Given more time and better access to resource materials, the choice of problem areas and the ratings given might have been different. It should also be noted the poloidal divertor has received considerable attention in conceptual reactor designs while the bundle divertor has received much less and the helical divertor none at all. More work on conceptual designs utilizing the bundle and helical divertors might lead to different conclusions.

G.A. Emmert
Group Chairman

TABLE 1

	Poloidal	Bundle	Helical
1) Forces on Coils	1	2[a] 3	1
2) Neutronic Shielding	2	2[b] 3	xx (1)
3) Power Consumption	2	2	1
4) Current Density	1	1 3[c]	1
5) Target Power Density	3	2/x[d]	3
6) Vacuum Pumping	2	2	3
7) Unipolar Arcs		Physics Question (common)	
8) Maintenance	3	3[e]	xx(3)[e]

Footnotes

a - "2" if B (stagnation) $\lesssim$ 3 - 3.5 T

b - "2" if normal coils

c - "3" if superconducting

d - Topology an advantage - but not yet adequately studied.

e - Difficult, but topology an advantage

WORKING GROUP E

PHYSICS OF DIVERTORS AND THE SCRAPE-OFF LAYER

This group was invited to discuss in detail various models of plasma in divertors and in the scrape-off layer and to consider the relevance of present models and how they can be extended.

Members: M. Keilhacker (chairman), A.H. Boozer, H. Classen, U. Daybelge, G. Fuchs, G. Haas, M. Harrison, K. Lackner, A. Mense, G.H. Miley, P.E. Stott, J. Wesson.

IPP
Garching

8.5.1978
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Summary of Working Group E on
"Physics of Divertors and the Scrape-off Layer"

The models available are:

a) Zero-dimensional balance equations for hydrogen and impurity densities (Garching, Argonne a.o.)
These models show the relative importance of certain divertor characteristics, like unload and shielding efficiencies, for the divertor performance.

b) One-dimensional diffusion equation for the scrape-off layer

$$\frac{d}{dx}\left(D_{\perp}\frac{dn}{dx}\right) = \frac{n}{\tau_{\parallel}} \longrightarrow \Delta = \left(D_{\perp}\tau_{\parallel}\right)^{1/2}$$

c) One-dimensional multi-fluid transport code (Oak Ridge, Jülich, Garching)
The energy loss to the divertor plates is described self-consistently, including sheath potentials and secondary electron emission. For particle and heat transport perpendicular to the magnetic field empirical coefficients are used.

d) Two-dimensional neoclassical kinetic theory (Hinton and Hazeltine, Daybelge and Bein).
Loss cone filled up by collisions only.

e) Two-dimensional two-fluid theory (Boozer).
Assumes isotropic pressure (enhanced filling of loss cone by micro-turbulence?). Diffusion not necessarily ambipolar on open magnetic field lines. Electrons and ions leave on different field lines.

What is needed is to connect the results of a model like e) to a one-dimensional multi-fluid code for the plasma interior.

The following physics should be included in these models:

a) Relation between divertor model and arcing

The divertor models predict a certain sheath potential. On the other hand arcing modifies the sheath potential and increases the impurity concentration.
Possibly arcing could be included by changing the boundary conditions at the divertor plates (e.g. fictitious secondary electron emission coefficient or sputtering by electrons).

b) Impurity dynamics
Radiation cooling by impurities has some adverse effects. It destroys the shielding efficiency (if the electron temperature falls below the ionization limit), reduces the heat load to the divertor plates and makes the scrape-off plasma more collisional.

Compared with the uncertainties of the models the uncertainties in the data base seem to be of minor concern. Exceptions: Reflection coefficients and cross-sections for charge-exchange between hydrogen and multiply charged impurity ions.

The following physics points were emphasized:

a) If sheath effects are classical (i.e. no arcing), then
- for large secondary electron emission one gets high electron heat loads over small areas
- for small secondary electron emission the electron heat flux is small but the sheath potential is large resulting in increased ion sputtering.

Therefore, for optimum performance the secondary electron emission has to be chosen to give the maximum tolerable heat flux to the collector plate (which depends on the plate material).

b) The two-dimensional two-fluid model resolves the flow into the divertor. The pressure gradient driving this flow gives rise to electric fields that pull impurities to the divertor plate.

c) For finite backstreaming (e.g. due to end plugging by neutrals) the flow into the divertor is subsonic. This results in improved screening efficiency.

It is important to experimentally check the scaling of quantities that determine the scrape-off layer and the performance of a divertor and to devise ways of improving these quantities.

Physics of Divertors and the Scrape-off Layer

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I. Introduction

Theoretical predictions of the various processes in the scrape-off and divertor regions and of the performance of divertors on tokamak plasmas have been made from a variety of points of view. The work by Hinton and Hazeltine /1/ and by Daybelge and Bein /2/ is based on neoclassical kinetic theory, whereas Boozer /3/ starts from the two-fluid equations. In the following we shall discuss simple zero-dimensional divertor models which, though not describing all the relevant processes correctly, are useful in developing an understanding of the relative importance of these processes in determining divertor operation (see also /4/ and literature cited therein).

In the first part we describe a model for plasma-wall-divertor interaction that is based on a zero-dimensional impurity balance equation and discuss results obtained with this model. In the second part the density profile in the scrape-off layer as derived from a one-dimensional diffusion equation is used to calculate various parameters (e.g. unload efficiency, shielding efficiency) that determine the performance of a divertor.

II. Plasma-Wall-Divertor Interaction

The operation of a divertor is specified by three main characteristic parameters:

- unload efficiency U,
- backstreaming ratio R_H, and
- shielding efficiency S.

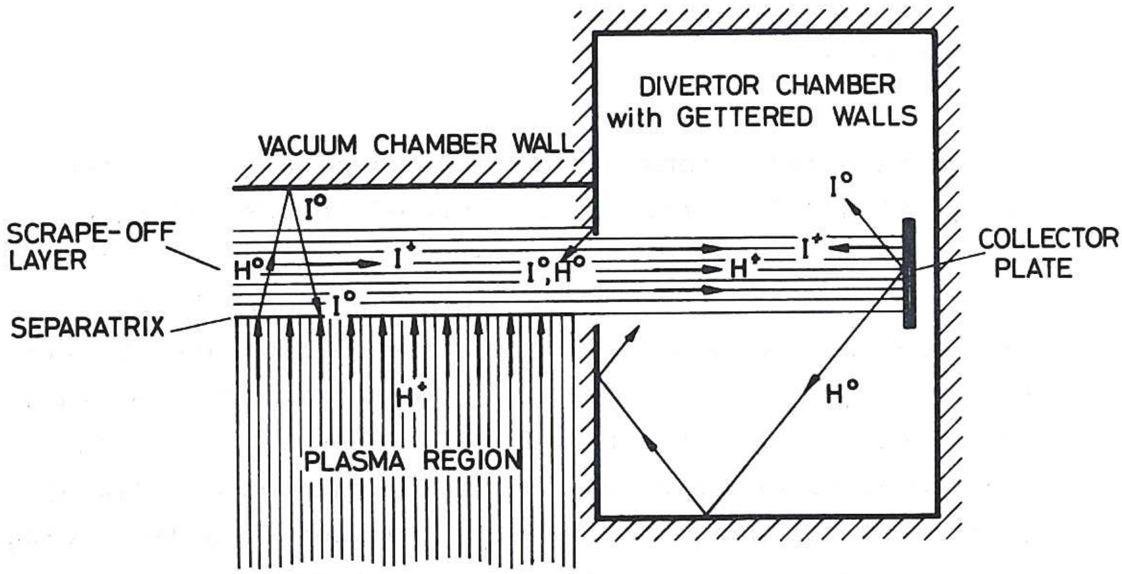


Fig. 1: Idealized representation of processes in the scrape-off and divertor regions.

A simplified representation of the processes in the scrape-off and divertor regions (see Fig.1) leads to the following impurity balance equation:

$$\dot{n}_I = \frac{n_H}{\tau_H} \Big\{ (1-U)(Y_H^L + \gamma_H \; Y_H^W)(1-S) + U \left[Y_H^D \, S_i \, \eta (1-S_f) + R_H \, \gamma_{H_2} \; Y_H^W \, (1-S) \right] + (1-R_H) \sum_m \alpha_m \, \gamma_m \, Y_H^W \, (1-S) \Big\} + \frac{n_I}{\tau_I} \Big\{ (1-U) \; Y_I^L \, (1-S) + U \; Y_I^D \, S_i \, \eta (1-S_f) - 1 \Big\} .$$

Here n and τ denote particle densities and confinement times, Y sputtering yields and γ the number of fast cx neutrals which bombard the wall per neutralized plasma ion. The subscripts H, H_2 and I relate to hydrogen atoms, hydrogen molecules and impurities, respectively, whereas the indices L, W and D indicate sputtering from the limiter, the wall and the collector plate.

The first line of the above equation describes the build-up of impurities caused by the part of the plasma impinging on the divertor slits. The second line represents the contribution by the plasma that enters the divertor and sputters the collector plate. A fraction $S_i\ \eta$ of the sputtered material becomes ionized in the plasma in front of the plate (S_i) and reaches the plasma chamber along the field lines (η). Part $(1 - S_f)$ of this fraction diffuses into the plasma. Of the neutralized gas, part R_H flows back into the plasma chamber and leads to cx sputtering. The third line of the equation describes the build-up of impurities connected with refuelling. Here α_m denotes the fraction that a specific refuelling method contributes to the total particle flux. The last line finally represents the contamination due to sputtering by impurity ions from the plasma. The impurity balance equation can be written in the form

$$\dot{c}_I = \frac{H}{\tau_p} + c_I \frac{I - 1}{\tau_I} ,$$

where $c_I = n_I/n_H$ is the relative concentration of impurity ions. The coefficient H describes all contributions to the contamination that are due to sputtering of the limiter and collector plates by plasma ions (including self-sputtering by metal ions) and of the wall by cx neutrals. The coefficient I describes the corresponding contributions due to sputtering by metal ions from the plasma.

This equation has the solution

$$c_I = \frac{H}{1 - I} \cdot \frac{\tau_I}{\tau_p} \left[1 - \exp - \left((1 - I) \frac{t}{\tau_I} \right) \right] .$$

For $I < 1$, which is usually the case, the impurity concentration, after a time of the order of the impurity confinement time τ_I, reaches the stationary value

$$c_{I,stat} = \frac{H}{1 - I} \cdot \frac{\tau_I}{\tau_p} .$$

Ion- CX- Sputtering	Unload Divertor $U=1$	Shielding Divertor $S=1$	No Backflow from Divertor $R_H=0$	No Divertor $U=S=0$
$Y_H^L + \gamma_H Y_H^W$	0	0	$(1-U)(1-S)$	1
Y_H^D	$S_i \eta (1-S_f)$	$\eta (1-S_f)$	$S_i \eta (1-S_f)$	0
$\gamma_{H_2} Y_H^W$	$R_H(1-S)$	0	0	0
$\sum_m \alpha_m \gamma_m Y_H^W$	$(1-R_H)(1-S)$	0	$(1-S)$	$(1-R_H)$
Y_I^L	0	0	$(1-U)(1-S)$	1
Y_I^D	$S_i \eta (1-S_f)$	$\eta (1-S_f)$	$S_i \eta (1-S_f)$	0

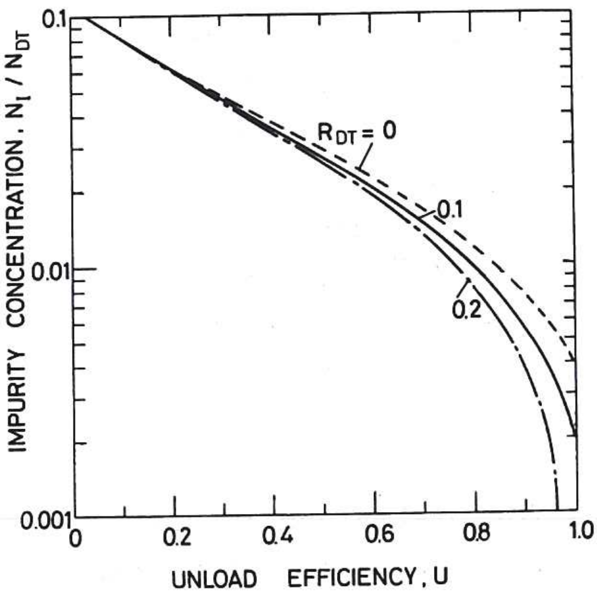
Table 1

To obtain a better insight into the importance of the various factors which describe the plasma-wall-divertor interaction it is worthwhile to consider some limiting cases, e.g. 100 % unload divertor ($U = 1$), 100 % shielding divertor ($S = 1$), no backflow from divertor ($R_H = 0$) and no divertor at all ($U = S = 0$). Table 1 gives a survey of the resepctive contributions to impurity build-up in these cases. The sums of the first four lines of each column yield the coefficients H, the last two lines the coefficients I.

Zero-dimensional balance equations for plasma and impurity densities as described above are very useful for determining - at least in a qualitative way - how the various divertor characteristics influence the impurity level.

The following examples, which are taken from W.M.Stacey et al. /5/, show numerical simulations of the steady-state impurity build-up in a tokamak reactor. In this study two modes of divertor operation are compared: the "unload" divertor (with characteristic parameters $U = 0 \div 1$, $S = 0.05$) and the "shielding-unload" divertor ($S = 0.5 \div 1$, $U = 0.85$). Sputtering yields characteristic of iron were used and wall recycling of the DT mixture and of the impurities was assumed to be 0.95 and 0.05, respectively. The cx neutrals from the plasma were assumed to have a temperature $T_{np} = 2 \cdot T_{edge}$, those from the scrape-off layer $T_{ns} = \frac{1}{2} \cdot T_{edge}$, T_{edge} being the ion temperature at the edge of the plasma.

The steady-state impurity concentrations plotted in Figs.2 and 3 are normalized and have to be multiplied with the relative particle confinement times. Figures 2a and b show results for the unload divertor, and Figs.3a and b for the shielding-unload divertor. In the case of the unload divertor the wall-sputtered impurity concentration is quite sensitive to the unload efficiency at large values of U (Fig.2a) and to the plasma-edge temperature (Fig.2b), but only moderately



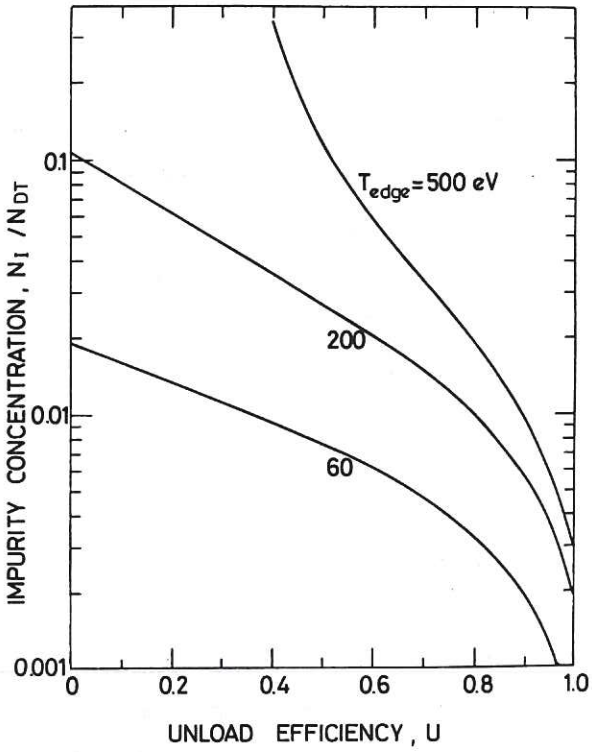
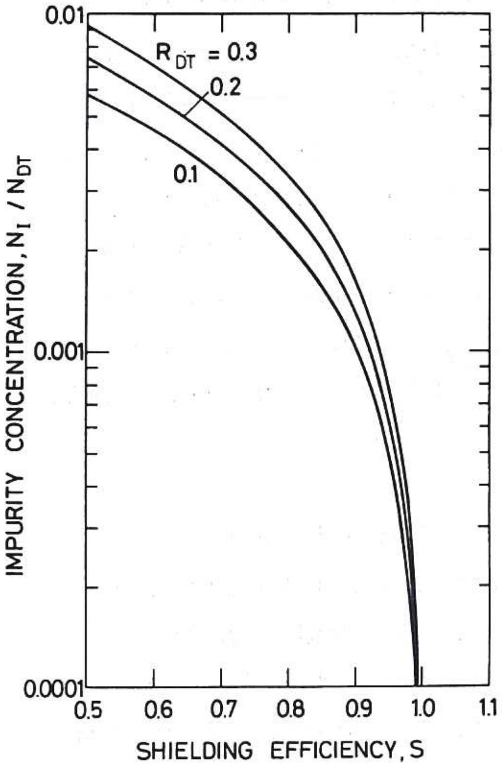


Fig.2: Normalized wall-sputtered impurity concentration as a function of unload efficiency U, with
a) backstreaming ratio R_{DT} ($S = 0.05$, $T_{edge} = 200$ eV) and
b) plamsa-edge temperature T_{edge} ($S = 0.05$, $R_{DT} = 0.1$ as parameters.



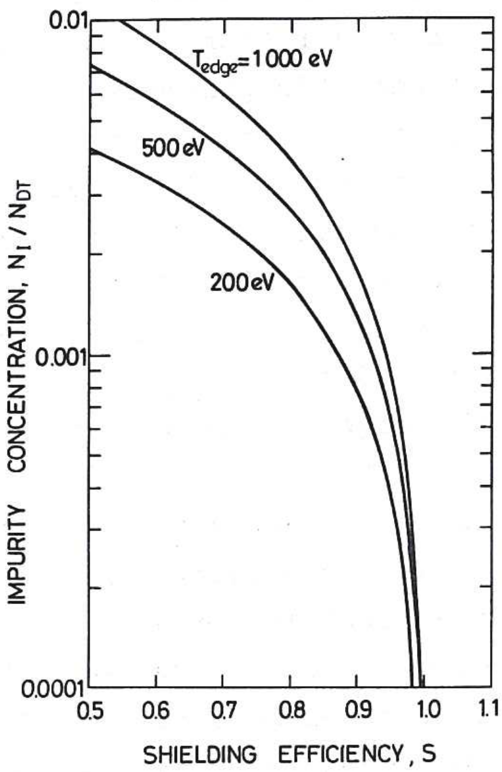


Fig.3: Normalized wall-sputtered impurity concentration as a function of shielding efficiency S, with
a) backstreaming ratio R_{DT} ($U = 0.85$, $T_{edge} = 500$ eV) and
b) plasma-edge temperature T_{edge} ($U = 0.85$, $R_{DT} = 0.2$) as parameters.

sensitive to the backstreaming ratio (Fig.2a). For the shielding-unload divertor the impurity concentration is extremely sensitive to the shielding efficiency at large values of S (Figs.3a and b). In general, the results show that a shielding-unload divertor has a greater potential for achieving a very low impurity concentration than an unload divertor.

III. Scrape-off Layer

1. Density profile

Various models have been proposed to describe the processes in the scrape-off layer. In the case that particle transport is governed by diffusion one usually considers a simple one-dimensional model in which plasma diffusion across the magnetic field (perpendicular diffusion coefficient $D_{\perp s}$) is balanced by particle flow parallel to the field lines into the divertor (particle loss time $\tau_{\parallel}$). In this model the two-dimensional effect of particle flow to the divertor is simulated by an absorption term in the particle continuity equation, which is then of the form

$$\frac{d}{dx} \left(D_{\perp s} \frac{dn}{dx} \right) = \frac{n}{\tau_{\parallel}} - n\, n_n \langle \sigma v \rangle_i \ .$$

The second term on the right-hand side, which describes ionization in the scrape-off zone, should be small for a working divertor and will be neglected in the following.

Assuming that $D_{\perp s}$ and $\tau_{\parallel}$ are constant across the scrape-off region, the density profile is given by

$$n = n_s \exp(-x/\Delta),$$

where $\Delta = (D_{\perp s}\, \tau_{\parallel})^{1/2}$

$$\text{and } n_s = \frac{\bar{n}\,a}{2\tau_p}\,\frac{\Delta}{D_{\perp s}} = \frac{\bar{n}\,a}{2\tau_p}\left(\frac{\tau_{\parallel}}{D_{\perp s}}\right)^{1/2}$$

are the width of the scrape-off layer and the plasma density at the seapratrix $(x = 0)$, respectively.

Apart from quantities that relate to the confined plasma (plasma radius a, average plasma density $\bar{n}$ and particle confinement time τ_p), the density profile in the scrape-off layer depends only on $D_{\perp s}$ and $\tau_{\parallel}$. According to one's prejudices about the relevant physics in the scrape-off layer, various choices for these quantities can be made.

a) Ambipolar flow with ion sound speed

In the "ion sound model" it is assumed that an electric sheath is formed in front of the neutralizer plates causing ambipolar plasma flow into the divertor with a flow velocity of the order of the ion sound speed, v_s. In this case $\tau_{\parallel}$ is simply given by

$$\tau_{\parallel} = L/v_s,$$

where L is the geometrical path length into the divertor.

This situation holds for divertors with no magnetic mirrors, e.g. for poloidal divertors with stagnation lines on the large major radius side. In a slightly modified way it also applies to divertors with magnetic mirrors (e.g. double inside poloidal divertor, bundle divertor) if the plasma in the scrape-off layer is collisional enough to maintain an isotropic velocity distribution, i.e. if particles are scattered by collisions into the loss-cone in a time shorter than their transit time into the divertor. In this case, however, only those particles that are not trapped (roughly a fraction $1 - (\frac{a}{R})^{1/2}$ for an inside poloidal divertor) contribute to the particle flux to the divertor, and the width of the scrape-off layer becomes correspondingly larger.

b) Mirror confinement

The situation is different if there is a mirror in front of the divertor and the scrape-off plasma is fairly collisionless. In this case a considerable fraction of the particles in the scrape-off layer is trapped (a fraction $\simeq (\frac{a}{R})^{1/2}$ for an inside poloidal divertor) and the particle flux to the divertor is determined by the rate at which collisions scatter these trapped particles into the loss-cone. In this "mirror confinement model" the particle loss time is approximately equal to the scattering time of trapped particles into the loss-cone, i.e.

$$\tau_{\parallel} = \tau_{90^\circ} \log M,$$

where τ_{90° is the 90° scattering time for the ions and M is the mirror ratio.

In practice, the anisotropic velocity distribution caused by the divertor loss-cone may be unstable to several microinstabilities, thus enhancing the scattering frequency and preventing a classical mirror confined scrape-off plasma.

One of the most important objectives of existing (DIVA, DITE) and forthcoming (ASDEX, PDX) divertor tokamaks is to investigate the scaling of certain quantities characteristic of a scrape-off layer (e.g. particle flow velocity, heat transport rate, density scale-length) and to compare it with the proposed models. So far experiments on FM 1 /6/ and DIVA /7/ indicate that the flow velocity into the divertor is about one-third the ion sound speed. The observed widths of the scrape-off layers in DITE /8/ and DIVA /7/ are consistent with the ion sound model and a perpendicular diffusion coefficient corresponding to 0.1 to 0.5 times Bohm diffusion. In DIVA the diffusion coefficient was also shown to have the functional dependence expected for Bohm diffusion (over a factor of 5 in parameter range) /9/.

2. Unload efficiency

If the density profile in the scrape-off layer is known, the unload efficiency of the divertor can be calculated from the relation

$$U = 1 - \exp\left(-W/\Delta'\right),$$

where W is the effective width of the divertor entrance slit and Δ' the density scale-length in the scrape-off layer projected into the divertor throat, i.e. $\Delta' = (B_p/B_p')\cdot\Delta$, B_p' being the poloidal field in the divertor throat and B_p the average poloidal field.

For $W/\Delta' = 4$, for example, a value that is easily attainable in most divertor designs, one gets $U = 0.98$, i.e. most of the outstreaming plasma goes into the divertor.

3. Neutral gas return from the divertor

The wide divertor entrance slit postulated by a high unload efficiency has to be compared with the requirement that only a small fraction of the neutral gas that is generated in the divertor by neutralizing the incoming plasma should return to the main vacuum chamber. The latter requirement calls for high pumping speeds that can only be achieved by getter pumps. If possible, the getter pumping should be supplemented by trapping of plasma ions in the neutralizer plates.

The fraction of neutral gas that returns from the divertor, the backstreaming ratio R_H, is then given by

$$R_H = \frac{C(1 - f_p)}{C + P} ,$$

where C is the conductance of the divertor throat, f_p the trapping efficiency of the neutralizer plates for plasma ions, and $P = f_n A$ the pumping speed (f_n is the intrinsic pumping speed, and A the area of the gettering surfaces).

4. Shielding efficiency

The shielding process in the scrape-off layer consists of two steps: first the impurity atom has to be ionized and then the ion has to be swept into the divertor. In order to shield the plasma core against wall-originated impurities the ionization process has to take place so far away from the separatrix that the impurity ions cannot diffuse into the confined plasma during their flight into the divertor.

In the following, we shall assume that the inward diffusion is sufficiently slow for all the impurity ions to be swept into the divertor. With this simplification the shielding efficiency is equal to the ionization probability

$$S_i = 1 - \exp - \left[\frac{\langle \sigma v \rangle_i}{v_I} \int_0^\infty n dx \right] ,$$

where $\langle \sigma v \rangle_i$ is the ionization rate and v_I the radial velocity of the incoming impurity atom.

As far as the scrape-off plasma is concerned, the ionization probability depends only on the area density $\int_0^\infty n dx$. Furthermore, since it can be assumed that the impurity atoms all come off the wall with the same energy kT_I, the ionization proba-

bility is larger for heavier impurities ($v_I = (kT_I/m_I)^{1/2}$).
It is interesting to note that the area density of the scrape-off layer

$$\int_0^\infty n dx = n_s \Delta = \frac{\bar{n} a}{2\tau_p} \cdot \tau_{\parallel}$$

depends only on the sojourn time of particles in the scrape-off region, $\tau_{\parallel}$ (apart from quantities that relate to the confined plasma). For $\tau_{\parallel} = L/v_s$ (ion sound model) and a fixed type of divertor (which determines L and M) the area density and hence the ionization probability depend only on the electron temperature in the scrape-off layer, T_e ($\int_0^\infty ndx \propto T_e^{-1/2}$).

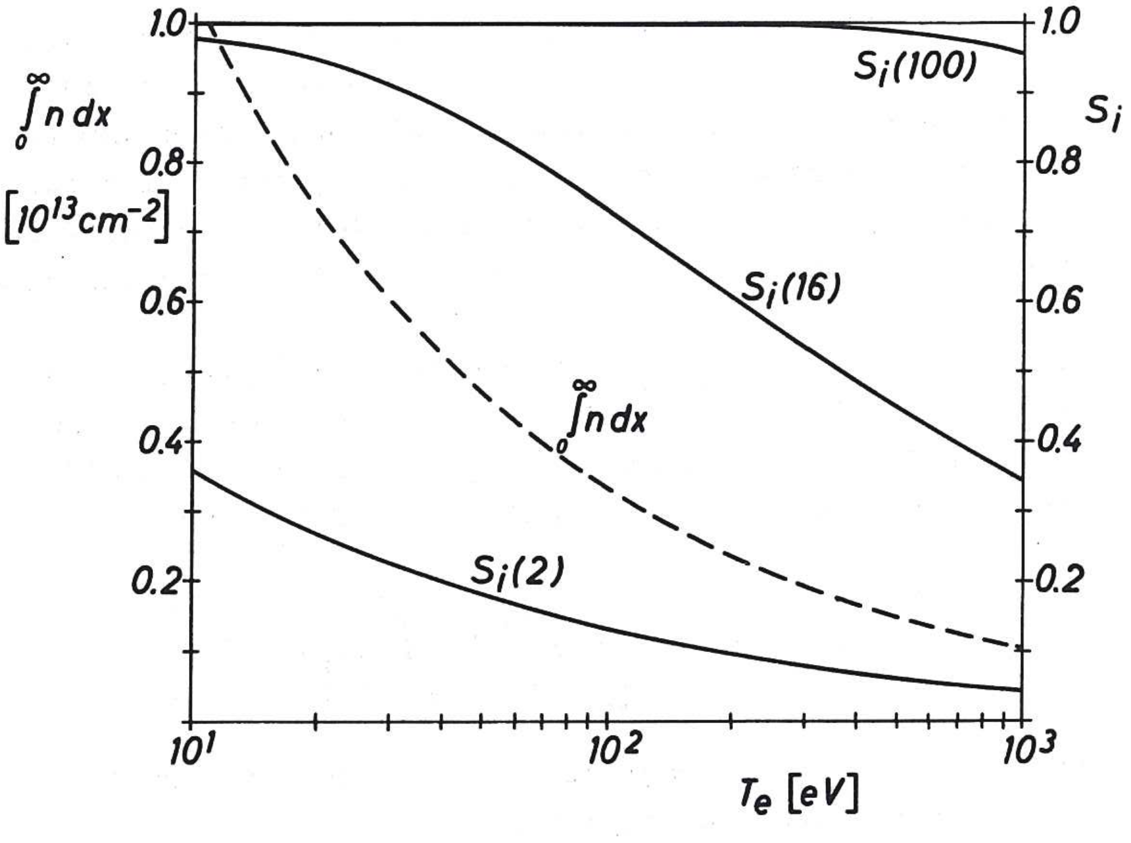


Fig.4: Area density $\int_0^\infty ndx$ and ionization probabilities for hydrogen $S_i(2)$, oxygen $S_i(16)$ and heavy impurities $S_i(100)$ as a function of the electron temperature in the scrape-off layer, T_e, for a poloidal divertor of ASDEX-size.

Figure 4 shows these dependences for a poloidal divertor of the geometry, dimensions and plasma parameters planned for ASDEX. In this example the impurities were assumed to have a radial velocity corresponding to 1 eV and values of 3×10^{-8}, 1×10^{-7} and 3×10^{-7} cm^3/s were used for the ionization rates of hydrogen (S_i (2)), oxygen (S_i(16)) and heavy impurities (S_i(100)), respectively.

Let us finally mention some possibilities of improving the shielding efficiency of the scrape-off layer.

- As we have seen above, it is advantageous to keep the electron temperature in the scrape-off layer as small as is compatible with effective ionization of the impurities. (A low edge temperature, of course, also helps to keep sputtering rates, and hence, the influx of impurities, small (see Figs. 2b and 3b).
- A longer path length into the divertor (e.g. as in the bundle divertor) increases the ionization probability. But this also increases the sojourn time of the impurities in the scrape--off layer and therefore the distance they diffuse into the plasma before reaching the divertor.
- Increasing the density in the scrape-off layer, e.g. by gas puffing, is certainly beneficial. This effect is believed to account for the improved plasma purity observed in tokamak experiments using gas puffing such as Alcator and Pulsator.
- A novel method of improving the shielding efficiency is the proposal /10/ to enhance the diffusion coefficient at the plasma edge by ergodization of the magnetic field lines. This is accomplished by superposing resonant helical fields on an axially symmetric tokamak equilibrium. It is claimed that this increases the area density by a factor of ten over that expected for an ordinary poloidal divertor.

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Summary of talk by A.Boozer, Plasma Physics Laboratory, Princeton, on the

Theory of the Poloidal Divertor+)

The theory of the poloidal divertor consists of three parts - the magnetic configuration, the electron dynamics, and the ion dynamics. The magnetic configuration has the following primary properties. First, if a magnetic field line is a distance δa from the separatrix (with a the plasma radius) well away from the x point, then near the x point the line is a distance $\delta^{1/2} a$ away from the separatrix. Second, the safety factor q has the form near the separatrix $q(\delta) \approx (q_o/2\pi)\ln(1/\delta)$ with q_o a normalizing q value formed using the maximum poloidal field occuring on the separatrix. Consequently, $q \lesssim 2\, q_o$ for $\delta > 10^{-5}$; so the safety factor is not large over physically significant distances despite being infinite on the separatrix. Third, in the absence of absolute toroidal symmetry, magnetic surfaces near the separatrix are destroyed. The width of this ergodic layer is roughly

$$\delta \approx nq_o \frac{B_\perp}{B_p} \exp\left[-\frac{\pi}{2}\left|\frac{nq_o}{4} - \frac{m}{2-\sqrt{2}}\right|\right]$$

with m and n the poloidal and toroidal mode numbers of the perturbation. The poloidal field B_p is the maximum on the separatrix and $B_\perp$ is the magnitude of the perturbation orthogonal to the unperturbed field.

The electron inertia is negligible and the electrons obey diffusion equations. The flow of electrons to the neutralizer plate is heavily controlled by a Debye length scale electric sheath near the neutralizing plates. Due to the conductivity of the neutralizing plate, the electron outflow does not balance the ion outflow field line by field line; only the integrated fluxes are equal. The width of the region of outflow of

+) Copies of a 15 page paper by Boozer were distributed.

the electrons to the neutralizing plate is the distance over which electrons can diffuse while flowing down the field lines.

The ions would be mirror confined in a divertor with the x point on the small major radius side in the long mean free path limit. However, the mirror distribution function is thought to be unstable; so microturbulence should make the pressure close to isotropic. The isotropy of the ion pressure implies a fluid theory of the ions is a reasonable approximation. The ion fluid equations (without ion-electron collisions) predict a characteristic scrape-off layer scale of an ion poloidal gyroradius. A non-classical electron-ion interaction could of course be strong enough to broaden the scrape off further. The flow out speed of the ions is controlled by the absorptivity of the neutralizer plate. The limiting flow out speed is sonic flow along the field lines. However, if there are neutrals or other end plugs in the divertor chamber or residual mirroring action in the presence of the microturbulence, the flow out rate can be subsonic. Indeed, experiments indicate a flow speed of only a third sonic. If both the flow out is subsonic and the scrape off layer is wide compared to a poloidal gyroradius, the ion inertia is negligible. Under these conditions, the plasma flow problem in a divertor configuration of a plasma column can be solved analytically. One obtains the interesting result that the entire flow across the separatrix occurs near the x point.

Discussion after talks by Keilhacker and Boozer

D.Meade emphasized that high unload efficiency and high shielding efficiency are independent divertor properties and briefly mentioned Princeton computer studies.

S.Gralnik asked about the flow of neutrals from the divertor chamber into the plasma chamber.
M.Keilhacker pointed out the neutrals in the divertor chamber could slow the plasma flow.
A.Boozer said the neutral backflow from the divertor could be reduced essentially arbitrarily but at the expense of divertor chamber complexity and size.

G.Emmert noted that the concentrated electron heat flux mentioned in Boozer's talk adds to the heat load problem. He also noted that if the electron temperature becomes too low in the scrape-off then the ionization of impurities is reduced and hence the shielding.

J.W.M.Paul asked if one wanted to destroy the electrostatic sheath which is expected near the neutralizer plate.
M.Keilhacker said this had not been discussed.

Y.Shimomura asked how T_e and T_i would be expected to scale in the scrape-off.
G.Fuchs replied that T_e was expected to be lower.

A.Mense questioned the existence of an explanation for the epithermal electrons observed in scrape-off layers.
Y.Shimomura said they were runaways from near the separatrix.

Y.Shimomura noted that in DIVA the breakup of magnetic surfaces near the separatrix had been observed using run-away electrons.

G.Emmert asked about relation between divertor and limiter theory and wondered if divertor experiments give us any data.
D.Meade noted the lack of limiter diagnostics but said comparism between theory and experiment should be made using the shape of the heat load found on the DITE neutralizer plate.

J.W.M.Paul pointed out the turbulent nature of the DITE scrape-off layer.

D.Meade said computer codes gave results which were roughly right for the density profile and the heat profiles should be compared. He said codes at Princeton were looking at the limiter problem.

J.W.M.Paul pointed out that reducing the aperture of the limiter or divertor improves DITE's performance and complicates comparisons.

P.Stott said theorists should be encouraged to get involved and not discouraged. He said the experiments must be improved to increase the interaction.

M.Okabayashi pointed out that fluctuations were not so important in FM 1 as in DITE; so simple theory might apply.

WORKING GROUP F

FURTHER EXPERIMENTS AND DIAGNOSTICS

This group was invited to continue the discussion on further experiments started by Group C, to consider what experiments would be needed to demonstrate the feasibility of divertors for reactors, and to consider the development of specialised diagnostics for divertor experiments.

Members: D. Meade (chairman), R. Behrisch, R. Clausing, S.J. Fielding, P. Harbour, T. Hsu, F. Karger, G.M. McCracken, H. Niedermeyer, M. Okayayashi, J.W.M. Paul, F. Sand, J. Sheffield, Y. Shimomura.

FUTURE EXPERIMENTS AND DIAGNOSTICS

Divertor Devices

The major divertor devices are listed in Table 1 according to divertor type; the devices are also divided into different generations:

1. First generation devices study divertor physics at low n, t and q (heat flux), and provide information for the design and operation of second generation devices.
2. Second generation devices study divertor physics at reactor-like plasma parameters and provide physics design data for reactor-divertor systems.
3. Third generation devices develop and test divertor technology for reactor-divertor systems and demonstrate the feasibility of reactor-divertor systems.

TABLE 1 - DIVERTOR DEVICES

GENERATION	POLOIDAL	TYPE	START	SPECIAL FEATURES
I	DIVA	SID	NOW	low n, t, q
II	T-12	2ID	NOW	low n, t, q
I	PDX	2ID	1978-79	low n, T, q
II	ASDEX	etc	1980-81	high n, T, q
	JT-4	2ID	1981	
III	JT-60	SOD	1981	
	TB-0	2ID	1983	long pulse
	PDX-II	SID	1982	elongation

SID = single inside divertor, 2ID = double outside divertor, etc.

GENERATION	BUNDLE	TYPE	START	SPECIAL FEATURES
I	DITE	Mk I	NOW	modest n, T, q
II	DITE	Mk II	1980	high n, T, q
	ISX-B		1980	high β, elongation
	TEXTOR		1981	
III	TFTR(?)		1983	

GENERATION	HELICAL RESONANT	TYPE	START	SPECIAL FEATURES
II	TEXTOR (?)		1981	
	RF			
II	TORE II (?)		1983	

Divertor Experiments

The experiments and diagnostics needed to supply divertor design information are listed below in outline form.

Divertor Effects on the Confined Plasma

Axisymmetric instabilities are a potentially serious problem for poloidal divertors, these instabilities were not important in the low-powered plasmas in DIVA and the General Atomic Octopole. PDX and ASDEX will use both passive and active stabilization on low β plasmas in 1979 and on high β plasmas in 1981. The reason axisymmetric instabilities are likely is that the experiments will simultaneously push plasma elongation ($\varepsilon \sim 1.5$) and divertor action. These instabilities are also sensitive to current and beta profiles which can be modified by neutral heating and particle fueling.

The magnetic separatrix near the edge of the plasma may have important effects on plasma stability. For example, the radial profile of the safety factor, q, is drastically affected by the separatrix. For the bundle divertor q is double valued which may lead to MHD instabilities. However, the strong shear for both cases may help MHD stability. In addition, V'' and connection length are affected by the separatrix. All of these effects need to be incorporated into a simple theoretical MHD model to determine the qualitative effects of the separatrix. Experiments should be prepared to look at MHD activity when q = n near the separatrix, and to look for ballooning effects at high β. These experiments should also be done as the separatrix is smeared using external perturbations.

The low pressure finite conductivity plasma in the divertor scrape-off may act like a close conducting wall and enhance MHD stability; a simple experiment to check this hypothesis is to cut-off the scrape-off plasma with a limiter while monitoring the MHD activity.

A potential MHD problem for the resonant helical divertor is mode coupling between the externally imposed m = 3 and plasma m = 2, causing plasma disruptions, etc.

Plasma transport due to ripple induced by the bundle divertor may be a serious problem for collisionless plasmas. Previous studies on DITE were done using collisional plasmas and no significant losses were found for the bundle divertor. In 1980, DITE Mk II with 150 kA and 2.5 MW of beam heating, and ISX-B with 150 kA and 3 MW of beam heating should be able to test for ripple effects on moderately collisionless plasmas. Simple ripple effects can be tested earlier on either PLT or ISX. These experiments need localized scannable diagnostics (e.g., charge-exchange and surface probes) to look for ripple escape along the bundle divertor null channel.

The divertor can also be used to modify density and temperature profiles by controlling edge recycling and using various forms of particle fueling and plasma heating. Nearly all the second generation devices will have pellet fueling (supplementary gas puffing) and neutral beam heating. In addition, ISX will have ECH heating and PDX may have some form of RF heating. Gas puffing at the plasma surface or through the neutralizer plate will be tried first. However, DITE results indicate poor penetration of the cold neutrals through the divertor scrape-off region, thereby indicating a need for pellet injection. Initial ISX experiments show penetration of pellets into the plasma, but multiple pulse injection is required. High power neutral beams (e.g., 6 MW into PDX) can fuel the plasma to $\sim 3 \times 10^{13}$ cm^{-3}.

One of the major objectives of these divertor-impurity control experiments is to develop an empirical scaling law for the impurity confinement time as a function of Z_j, n(r), T(r), etc. In addition, experiments are needed to simulate helium ash transport in a Z = 1 plasma with variable density and temperature profiles. Helium could be injected with beams or by gas puffing; a diagnostic detection system needing development since the helium will be fully stripped in the plasma core.

The importance of divertor control of impurities during plasma initiation and start-up will be studied on PDX and ASDEX.

Diagnostics

Scrape-Off Plasma Diagnostics

The operation of the divertor and its effect on impurity control, particle pumping and energy removal is determined by the plasma parameters in the divertor scrape-off. The key parameters and diagnostics are listed below. Profiles are in terms of radial, r, and parallel, l, co-ordinates.

$T_e(r,l)$ - 1 to 300 eV

Thomson scattering (ASDEX, PDX)

Langmuir probes (PDX, ASDEX)

Electron cyclotron emission and absorption (DITE, PDX)

Energy analyzer (DIVA)

$T_i(r,l)$ - 1 to 300 eV

Energy analyzer (DIVA)

Neutral beam charge-exchange plus low energy detection

H_α doppler broadening

$n_e(r,l)$ - 10^{11} to 10^{13} cm^{-3}

Langmuir probes

Thomson scattering

Lithium neutral beams (ASDEX)

Microwaves

$n_z(r,l)$ - 10^8 to 10^{11} cm^{-3}

Vacuum ultraviolet spectroscopy with special scan chords

Resonance fluorescence using dye laser (Jülich)

Surface analysis probes (PDX, ASDEX)

$n_n(r,l)$ - 10^8 to 10^{11} cm^{-3}

H_α emission

Resonance fluorescence of H_α (DITE '79) and later L_α

$\phi(r,l)$ - 1 to 100 V

Langmuir probes

Heavy ion beam probe

Inject impurities, measure energy due to potential along B

$V_{\parallel p}$ - 10^6 to 10^7 cm/s

Directional probes (DIVA)

Energy analyzer (in divertor or on a probe)

Time of flight after gas puff

$V_{\shortparallel_Z}$ - 10^5 to 10^7 cm/s

Same as for $V_{\shortparallel_p}$

Doppler shift requires special scans

First Wall Diagnostics

$\phi_p^{\pm}$ (Incident and reflected plasma ion flux)

Incident fluxes can be measured by looking at charge-exchange neutral fluxes, special detectors need to be developed for below 100 eV such as the low energy neutral detector of Cohen, et al. The thermal desorption probe developed by McCracken is also useful for determining fluxes in the low energy region with reduced time resolution.

The retention of H and D and their subsequent release is an important factor in determining the plasma-wall interaction such as recycling. Nuclear probes can be used to measure H retention and T inventory, insitu techniques need to be developed to monitor the T inventory.

$\phi_Z^{\pm}$ (Impurity flux to first wall)

Insitu surface analysis stations with probes at the first wall can measure the accumulation of surface impurities while radioactive tracers can be used to measure wall erosion rates.

A very important but difficult experiment is to measure directly the energy and angular distributions of impurity atoms that leave the wall. Resonance fluorescence scattering can measure small neutral atom densities but a technique is needed to measure the energy distribution. The energy distribution can be indirectly inferred from measurements of neutral atom penetration if the plasma parameters are known.

$\phi_E^{\pm}$ (Energy flux)

Traditional diagnostics such as X-ray, UV, and charge-exchange spectrometers give data on the energy distribution of particles incident on the first wall. Scannable bolometers are also very useful in determining the spatial distribution of the source of energy while infra-red TV and thermocouples can give time resolved information on the spatial distribution of energy on the first wall.

Divertor Chamber Diagnostics

Many first wall diagnostics can also be used on the divertor neutralizer plate.

$q(r)$ (Energy deposition)

The energy deposition profile can be measured with infra-red TV as has been done on DITE and will be done on PDX. A movable gridded analyser can measure the energy distribution of the incident particles (PDX), while movable colorimeter probes (DIVA) can also give time resolved energy profiles.

$\phi_z^{\pm}$ (Impurity flux)

Mass and energy analyzers can give mass, charge state and energy of incident impurities. Surface analysis samples can be embedded in the neutralizer plate or nearby and then retracted to be analysed by Rutherford backscattering, scanning electron microscope, Auger spectroscopy etc.

The direct detection of erosion can be accomplished by using radioactive or special material on the neutralizer plate. Arcs on the neutralizer plate can be a significant source of impurities, and techniques need to be developed to detect arcs. Large arcs can be detected with TV cameras or after the fact with visual inspection using microscopes.

$\phi_p^{\pm}$ (Particle flux)

The same diagnostics for ϕ_p at the first wall are applicable to the divertor. In addition the gridded analyzer, and the build-up of gas in a chamber that traps a portion of the incoming plasma will measure particle flux. Also, simple gas pressure measurements in the divertor will be needed to determine pumping speeds and gas flow-back rates.

Sheath Measurements

The electrostatic sheath at the neutralizer plate has a large effect on energy flow to the plate and particle sputtering from the plate. The sheath can be measured by using the divertor plates as double Langmuir probes. In addition, heavy atom beam probes and impurity flow can be used to measure the sheath potential directly.

Experiments with Divertor Tokamaks

Develop empirical impurity generation and transport laws that model divertor action and can be used to predict divertor operation on large tokamaks, therefore these experiments should be done on second generation divertor tokamaks with plasma parameters similar to reactors.

Verify impurity control by:

1. Measuring n_z in the plasma core for hot-ion plasmas with high power density in the divertor.

2. Varying divertor field strength or moving a limiter to continuously vary the divertor from off to on.

3. Inject impurities near plasma surface and in divertor to verify impurity control. Use radioactive tracers from limiter, wall and divertor to follow impurity motion.

Develop techniques to reduce energy density in the divertor such as:

1. Remote gas blanket (PDX)
2. Hydrogen cross jet (Jülich)
3. Move separatrix by modulating divertor current
4. Move the neutralizer plate (DITE)
5. Use coils to spread field lines at neutralizer
6. Use external EXB drift to move plasma
7. Angle the divertor plate
8. Use high technology cooling to allow high energy flux
9. Vary the electron secondary emission coefficient to affect the sheath

Develop high efficiency energy recovery system using high temperature, MHD or direct recovery.

Determine required pumping speeds, allowed pressure, particle throughput and allowed retention for different modes of divertor operation.

Develop pumping system suitable for reactors, possibilities include:

1. Regenerable getters (TFTR)
2. Cryocondensation
3. Cryosorption
4. In situ Vac Ion
5. Liquid lithium

Develop helium pumping, and helium-hydrogen separative system.

<u>Summary of present and proposed divertor experiments.</u>

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The workshop gave for the first time physicists and engineers working on divertors in Europe, Japan, and the USA an excellent opportunity to come together and to inform each other about work performed, work planned, about the associated problems, and about personal views how to solve them.

Problems were discussed from the different areas i.e. plasma transport theory, plasma stability, plasma diagnostics, surface physics, vacuum technology, target technology, magnetic design, coil design, mechanical engineering, stress analysis of the housing, over all design of experiments, conceptual design studies of reactor, neutronics, maintenance and radiation damage in solid materials. One of the outstanding features of the workshop was the attempt to break down this list into manageable pieces. This seemed to be a difficult problem in the sense of a common acceptance because of the different views of people in planning, people designing and building experiments, and experimenters.

Conceptual design studies in particular for reactors are easily affected by the temptation of the "grand vision" as well as by the exclusive search for "knock out" conditions. Designers and builders of approved experiments are working hard to keep to schedule.

To some extent, plasma physicists are handicapped by the restricted performance of the running machines, limited machine time and lack of appropriate diagnostics. The existing results from machines like C-Stellerator, DIVA and DITE are very encouraging and were essential for the discussions during the workshop. The DITE results in particular showed that inspite of all the discussion on topology problems of the magnetic fields, a bundle divertor works quite well. This opens an interesting option for reactor designers.

It is hard to imagine that all problems piled up during the workshop could be tackled in the near future.

This would require money and man power (> 100 my/y world wide) which are not available at present. A partial solution of isolated problems might even be not very helpful, because some of them become crucial ones in special combinations. It is recommended to intensify the detailed design work of divertors for large tokamaks (JET, JT 60) under construction although these divertors might not be built. A dedicated problem list resulting from such an attempt could be a good guide line to allocate the essential problems to be solved in the near future.

The following information could be expected:

- stresses in the coils and structure
- shape of coils and feeds
- limitations on magnetic field and pulse length
- loads to neutralizer
- pumping requirements
- tritium inventory
- power requirements

Another class of information can be expected from the experiments in progress or under construction:
- β limits
- kind of transport in the scrape-off layer
- thickness of the scrape-off layer
- unload efficiency
- scrape-off efficiency
- tolerable field ripple

The machines are listed in table I and II. The given values reflect what information was available during the workshop. Missing information does not indicate that it does not exist.

The bundle divertor experiments as DITE, ISX B and TEXTOR are in particular well suited to test novel pumping schemes, and neutralizers, as well as materials for neutralizers. TEXTOR, a medium size TOKAMAK, being somewhat later than the other experiments, may even try novel divertor schemes as the Helical Divertor.

It is a pleasure to thank the Culham Laboratory and its scientists for organizing this workshop.

Character	Description
BS	Single bundle divertor
BD	Double dundle divertor
HQ	Helical divertor for q = 4
PDI-C	Poloidal divertor, inside, double, for circular cross - section
PDI-D	Poloidal divertor, inside, double, for D-shaped cross-section
PDO	Poloidal divertor, outside, double
PDI-PDO	Two poloidal divertors inside, and two outside
PSI	One poloidal divertor, inside
PSO	One poloidal divertor, outside
TS	One toroidal divertor
NPI	Neutral particle injectors
ICRF	Ion cyclotron resonance heating
ECRH	Electron cyclotron resonance heating
CI	Cluster injectors
GP	Gas puffing
P	Pellet injectors

TABLE 1

Divertor Experiments

Experiment Divertor	R m	B_T (o) T (%) B(a)/BD	I_p MAT ID	a m Δ	< Te > kev sTe	< Ti > kev sN	< N > cm^{-3} sN	τ_{FT} sec τ_D	Additional-heating (MW) Te, Ti (kev)	Refueling	Comissioning
ASDEX	1,65	2.8	0.5	0.4	1	0.75	$3\cdot10^{13}$	5	NPI, 2,5	NPI, CI	1979
PDi-C		1.24	0.36	10^{-2}	0.1	0.1	$3\cdot10^{12}$	5	2 , 2	GP,P	
DITE	1.17	1/1.5/2.8	.05/-/.2	.2/-/.26	.2/7/7	.1/-/-	$5\cdot10^{12}$/-/-	.6/.6/.6	NPI/1.2/-/2.4	-	76/78/80
BS(MKI,Ia,II)		2	- /-/.6	0.07	0.025	-	10^{12}	.1/-/.2			
DIVA	.58	2	0.053	.09	0.2	0.3	$8\cdot10^{13}$	0.2	-	-	1974
PSI		1.5	0.06	-	< 0.1	< 0.06	-	0.05			
C-Stel	1.09	3	0.002	0.05	0.02	0.02	$2\cdot10^{13}$	0.01	ICRF, 0.02	-	1950
TS		-	-	10^{-2}	0.015	0.015	10^{13}	0.01			
FM -1 - Spherator	0.9	3	0.03	0.2	10	2	10^{11}- 10^{12}	DC	-	-	1971-1973
PSI		2	0.2	10^{-2}	0.005	0.002	10^{10}	DC			
ISX B	0.9	1.8	0.2	0.25 x 0.5	0.38	0.26	$2\cdot10^{13}$	0.3	NPI < 3, ECRH < 2	GP,P	-
BS		2.6	1.5	7	-	-	-	0.3	3 3		
IT 4	1.45	3	1	0.54x0.65	_ 2	0.6	10^{14}	1	NPI,6/RF,2 5 5	GP	1981-1982
PDI-C,PDI-D		-	-	-	-	-		1			
JT 60	3	4.5	3	1	-	-	-	5	NPI,20/RF,20 5 - 10, 5 - 10	-	1983
PSO		-	-	-	-	-	-	5			
PDX I PDi- PDO-C	1.4	2.5	0.5	0.5	0.5	0.5	$3\cdot10^{13}$	1	NPI, 6 2,2	GP, P	1978 0.5MW OH 1979 6 MW NP
PSi-C, PSO-C		2	1	$2\cdot10^{-2}$	< 0.1	< 0.1	$2\cdot10^{13}$	1			
PDX II	1.6	2.5	2	1 x 0.6	1.0	1.0	$3\cdot10^{13}$	1.5	NPI 10-20 10 10		1982 <N>=$2\cdot10^{14}$+ N
PSI - D		2	-	0.03	0.05	0.05	$2\cdot10^{13}$	1.5			
T 12	0.36	0.8	0.04	0.9x0.14	0.3	-	$3\cdot10^{13}$	0.05	-	-	
PDI-D		-	-	$5\cdot10^{3}$	0.02	-	-	0.05			
TEXTOR - B	1.75	2.6	0.7	0.5	0.8	0.7	$5\cdot10^{13}$	3	NPI 5 2 2	P,GP	1982
BD		2.5	1.1	$7\cdot10^{-2}$	< 0.1	< 0.1	$2\cdot10^{12}$	0.2			
TEXTOR - H	1.75	2	0.5	0.5	0.8	0.7	$5\cdot10^{13}$	3	NPI 0.6 0.8 0.8	GP	1981
HQ 4		-	0.1	0.05	< 0.05	< 0.1	10^{12}	3			

Divertors

Experiments	Scrape off Layer			Chamber		Pumps 1/sec
	$S\eta(Z>8)$	$S\eta(Z<8)$	$u\eta$ (%)	walls	neutralizer	
ASDEX	100	> 70	> 70	SS,AL	Ti-allay	6 10^6
DITE	75	50	30	SS	Mo or Ti	-
DIVA	75	50	-	SS	2kW/cm^2 Ti honey comb	-
C-Stell.	99	90	99	SS	SS	10^3
FM-I	-	-	-	SS	Ti plates	$4 \cdot 10^3$
ISX-B	-	-	-	SS	Zr/Al, Ti	-
JT 4	-	-	-	SS + Mo	Mo plates	-
JT 60	-	-	-	Mo + SS	Mo plates	-
PDX I	99	90	> 95	SS	Ti plates	$5 \cdot 10^5$
PDX II	99	90	> 95	SS	Cu, gas	$2 \cdot 10^5$ Cryo
T 12	-	-	-	-	-	-
TEXTOR-B	> 75	> 50	> 30	SS	Cu, He-gas Litt powder	> 10^3
TEXTOR-H	-	-	-	SS	Mo, W	$6 \cdot 10^5$

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