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RIJNHUIZEN - JUTPHAAS - NEDERLAND

WORKSHOP
ON COLD-BLANKET RESEARCH
JUTPHAAS 2-5 MAY 1977

COLLECTION OF ABSTRACTS

Rijnhuizen Report 77-103

ASSOCIATIE EURATOM-FOM
FOM-INSTITUUT VOOR PLASMAFYSICA
RIJNHUIZEN - JUTPHAAS - NEDERLAND

May 1977

WORKSHOP ON COLD-BLANKET RESEARCH

held under the auspices of the Euratom Tokamak Advisory Group

FOM-Instituut voor Plasmafysica
Jutphaas - Nieuwegein, The Netherlands
2-5 May 1977

- List of lectures presented
- Collection of abstracts
- Conclusion of rapporteurs

Rijnhuizen Report 77-103

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* For an abstract of this lecture the reader is referred to abstract 1 by B. Lehnert.

CONCLUSIONS OF THE WORKSHOP ON COLD-BLANKET RESEARCH

JUTPHAAS, 2-5 MAY 1977

Rapporteurs: F. Engelmann, A. Gibson, G. Grieger, O. Klüber, B. Lehnert and L.Th.M. Ornstein.

1. The objective of the Workshop was to identify and discuss cold-plasma blanket systems to achieve the following ends:
   1.1. In order to minimize the bombardment of the walls by hot neutrals the plasma should be impermeable. This requires a density edge-thickness product of $\overline{n\Delta} > 10^{15}$ cm^{-2}.
   1.2. To prevent the accumulation of impurities in the interior of the plasma.
   1.3. To ensure the exhaust of the α-particles produced in fusion reactions.
   1.4. To ensure refuelling of a reacting plasma by inward diffusion.

2. The Cold-Blanket is a plasma blanket rather than a gas blanket because the neutral density at the wall is expected to be less than the ion density in the edge region of the plasma. For example, in a tokamak reactor with a toroidal field (B) of 50 kG, an edge density (n_a) of 10^{14} cm^{-3}, and an edge temperature (T_a) of about 1 eV, the neutral density (n_n) at the wall is constrained to be below 10^{13} cm^{-3}. In a high-field reactor (say B ~ 100 kG; $n_a \sim 4\cdot10^{14}$ cm^{-3}; $T_a \approx 1$ eV) the neutral density is constrained to be below 10^{14} cm^{-3}. This limit arises from considerations of the balance, in steady state, between the outward diffusion flux of ions and the inward flux of neutrals for the case of 10 times Pfirsch-Schlüter diffusion in the edge region (yielding a scaling $n_n \propto n_a^3 q^2/B^2$).

3. Tokamak discharges have already been established which are impermeable to neutrals ($\overline{na}$ approaches 10^{16} cm^{-2} in Alcator). A clear qualitative indication of this is the disappearance of the high-energy charge-exchange neutral flux from the central region. Whether or not this shielding alone produces a sufficient reduction of the wall bombardment by energetic neutrals to adequately restrict impurity production, remains to be seen and will depend on the wall properties.

4. Calculations using the full collisional transport model indicate that steady states can develop with no important impurity accumulation in the plasma interior, and with fluxes that are such that plasma refuelling should be possible.

5. Simulation calculations for the next generation of large tokamaks using a particular transport model, indicate that the plasma edge profile can be controlled to reduce the production of sputtered impurities to an acceptable level. These methods of profile control are based upon the introduction of radially dependent energy and particle sources. A great deal of freedom still remains to optimize the choice of these sources (neutral injection, RF-heating, skin heating). Beyond this, the possibility exists of using azimuthally localized sources to influence the toroidal flows and hence the transport behaviour. These methods of profile control demand a certain expenditure of power. In the cases simulated, considerably improved impurity control was obtained for modest power.

6. The profiles established in these calculations are essentially model-dependent, so that while the results are encouraging, they cannot be confidently applied to a reactor. Thus, as in other fields of tokamak research, further progress depends on the development of transport models which are experimentally validated in the relevant parameter regime. One example of the deficiency of present transport models is that there is no universally accepted explanation of the density build-up by gas puffing into the impermeable Alcator.

7. These methods of impurity control require a small fraction of the radial space to accommodate the cold-plasma layer. This reduction of aperture is a worthwhile price to pay for good impurity control.

8. Refuelling with such a system can be envisaged through the feeding of gas into the outside layers of the system. The problem of exhaust is, however, more complicated. If the cold-blanket scheme works as predicted in the model calculations, then α-particles generated by fusion will be transported to the cold outside layer. The question of how these α-particles can be removed from that layer remains to be discussed. It is conceivable that simple gas flow to pumping ports will suffice, though this will certainly lead to difficult gas handling problems. However, at present it is not possible to exclude the possibility that more complicated systems will be necessary, in the limit the cold blanket might have to be replaced by a

divertor with a controlled scrape-off layer.

9. In addition to the lower limit on the impermeability parameter $\overline{na}$ (certainly greater than 10^{15} cm^{-2} and probably of the order of 10^{16} cm^{-2}) there is also an upper limit (of the order of a few times 10^{16} cm^{-2}) if neutral injection heating is to be possible. Furthermore, an upper bound for $\overline{na}$ may also be imposed by the hydrogen radiation losses from the outside layer (an effect of this type was observed in RINGBOOG I). It must be emphasized that the requirements imposed at the plasma edge lead to limitations also of the heat flux entering into this region, and it is important that these limitations can be fulfilled in the relevant parameter range.

10. The stability of these systems with low edge temperatures requires further consideration. Non-ideal effects may be important, as may questions of thermal stability.

11. The presence of a limiter and of localized gas inlet sources in present-day tokamaks introduces a deviation from axisymmetry which could lead to difficulties in extrapolation to reactors.

12. The Communities' experimental programme of research in this area can be discussed in terms of the tokamaks which are available and planned. These are listed below, together with measured (x) and estimated (+) values of $\overline{na}$:

device	operating	$\bar{n}(cm^{-3})$	a(cm)	$\overline{na}(cm^{-2})$
Pulsator	yes	10^{14}	10	10^{15} (x)
Alcator	yes	5×10^{14}	10	5×10^{15} (x)
DITE	yes	10^{14}	26	2×10^{15} (x)
TFR-600	1977	$> 10^{14}$	23	$> 2\times10^{15}$ (+)
FT	1977	5×10^{14}	20	10^{16} (+)
RINGBOOG II	1977	10^{14}	10	10^{15} (+)
Textor	1981(?)	5×10^{13}	50	2×10^{15} (+)
Torus II	1981(?)	10^{14}	90	10^{16} (+)
JET	1982(?)	10^{14}	125	10^{16} (+)

In the period up to 1980 a number of machines will be available with $\overline{na}$ of the order of 10^{15} cm^{-2} with 'a' between 10 and 25 cm. However, only one machine (FT) with $\overline{na}$ of the order of 10^{16} cm^{-2} will operate within the Community. One of the above machines (RINGBOOG II) is specifically designed for cold-blanket research. The programmes of the other machines will permit only global rather than detailed investigations of the cold blanket (although DITE is committed to a programme of plasma-wall interaction study). Consequently, the study of strongly impermeable plasmas in this period will only occur as a part of the FT programme and will be constrained by other demands and, maybe also by the available pulse length and diagnostic access.

In the period after 1980 the larger machines should become available, permitting studies up to the same values of $\overline{na}$ (10^{16} cm^{-2}) as in FT, but at the opposite extreme of smaller n and larger a (to confirm that indeed, only the product $\overline{na}$ is important).

Furthermore, we expect to get relevant information from machines outside the Community, such as PLT and T-10, as well as guidance from model experiments, such as those in progress in Stockholm.

Provided all the machines listed come into operation as assumed above and provided the necessary emphasis is given to profile control and cold-blanket studies, it would seem that adequate information in the effectiveness of these techniques for impurity control and fuelling should become available on a 5 to 7 year time-scale. However, it should be noted that until TORUS II or JET becomes available, full studies of the $\overline{na} \approx 10^{16}$ cm^{-3} region will probably not be possible. It follows from this that TORUS II should have as a main aim to study the topics of profile control and cold-blanket behaviour. In so far as the study of plasma-wall interaction and impurity control is a stated JET objective, these topics will also form a part of the JET programme.

13. The development of diagnostics for the plasma edge region is important to all tokamak programmes, but is especially essential for programmes concentrating on cold-blanket studies. It is therefore important that sufficient resources be devoted to diagnostic development. Examples of required development areas are: edge profiles of the neutral and impurity density, energies of neutrals and particle fluxes. Diagnostic development (e.g. fluctuation measurements) taking place in the general tokamak programme are also important here for understanding the transport process which determines profiles and fuelling.

14. Two options present themselves for the continuation of cold-blanket research.

14.1 Option 1

The construction of a new tokamak to be devoted exclusively to cold-blanket research, aiming at an $\overline{na}$ value of $> 10^{16}$ cm^{-2}.

14.2 Option 2

Establish a European Cold-Blanket Task Force with a nucleus formed from the RINGBOOG II and Stockholm groups using their own experiments and experience as a basis for the following investigations:

- a limited study of edge behaviour and refuelling on FT;
- a detailed cold-blanket programme on TEXTOR and/or TORUS II aiming to begin to produce results in 1982;
- a major programme on JET, in parallel with and extending beyond the TEXTOR/TORUS II programme, but directed to demonstration rather than exploratory experiments.

This task force should play an essential part in the formulation of the experimental programmes of the machines on which it works.

Option 1 is to be preferred from the point of view that it would devote the expertise of an existing team on an existing site (Jutphaas) to a machine specifically dedicated to cold-blanket research. This option increases the overlap of community programmes. At present no resources have been identified for such a programme.

Option 2 is very desirable from a planning point of view, but may be put in jeopardy by the demands placed on staff by the high degree of mobility required.

1. MAIN FEATURES AND POTENTIALITIES OF GAS-BLANKET SYSTEMS

by

B. Lehnert

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A review is given of the features and potentialities of gas-blanket systems, with respect to plasma equilibrium, stability, and reactor technology. The treatment is mainly concentrated on quasi-steady magnetized plasmas confined at moderately high-beta values. In these systems the plasma becomes separated from the blanket only when the ion density is chosen far inside the impermeable regime. Steady solutions exist within limited parameter ranges. The pressure and density profiles are affected by ionization of neutral gas, by the presence of various atom species and impurities, as well as by Nernst, toroidal, and anomalous effects. Further, the partially ionized boundary layer becomes diamagnetic, the blanket pressure does not balance the plasma pressure, the heat balance determines the boundary layer thickness, and the strongly inhomogeneous distributions of the plasma and the neutral gas parameters in space modify the stability properties, especially on account of an existing boundary layer. The gas-blanket approach has certain important potentialities as fusion reactor, e.g. in connection with the desired densities and dimensions of full-scale systems, refuelling as well as ash and impurity removal, and stability.

This abstract covers also the lecture on the stability of gas-blanket systems given by B. Lehnert.

2. STEADY STATES ON TRANSPORT TIME-SCALES

by

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For the cold-plasma blanket to be a useful refuelling device, appropriate steady states of the plasma on a time-scale longer than the particle confinement time must exist. The implications of this condition are displayed. It is concluded that for treating the cold-plasma blanket problem realistically from a theoretical view point, more detailed knowledge about the actual anomalous transport properties of the plasma is required.

3. EXPERIMENTAL APPROACH TO COLD-BLANKET RESEARCH

The RINGBOOG Team* presented by L.Th.M. Ornstein
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The rationale of our work is the protection of plasma against the contaminating interaction with the walls by surrounding the hot core with layers of cold plasma and neutral gas. If the outer layers are of sufficient width and density an impermeable blanket is obtained. In this blanket the energy of the neutral charge-exchange flux from the hot core is moderated to such an extent that the wall is only reached by particles with energies below the sputtering threshold. This principle has been confirmed experimentally in the operation of tokamaks with gas injection, e.g. Alcator. The density in these experiments is found to increase strongly with the gas injection. Processes responsible for the observed density increase up to 10^{15} cm^{-3} (which cannot be explained by classical inward diffusion of neutrals) may prove to be a powerful method to fuel thermonuclear plasmas. In the tokamak experiments the energy confinement time increases linearly with density - apparently the anomalous energy loss through the electrons disappears - and, consequently, the temperature stays high (order of 1 keV).

In our experiment RINGBOOG a toroidal discharge is struck in hydrogen at relatively high filling pressures. This leads to densities similar in magnitude to the upper limit reached in Alcator. Notwithstanding the fact that the ohmic dissipation is high, the temperature stays low. The energy balance of the core is dominated by the emission of hydrogen Lyman lines. The resonant radiation is reabsorbed in the dense outer layers where it leads to additional ionization. This effect dominates the local particle balance so that hollow (unstable) density and pressure profiles are found. The energy- and particle-balances in the blanket region are studied numerically; radiation, ionization as well as diffusion are taken into account. A confirmation of the effect described above is given for a variety of parameters.

Generally, the possibility of shielding hot plasmas by cold blankets may be limited by the dominant role of radiation in the transition layers, since such layers would be similar in character to our RINGBOOG plasma.

In order to obtain stable discharges enclosed by cold blankets, the RINGBOOG facility is at present being rebuilt. This will enable us to obtain clean plasmas at lower filling pressures. Apparently, two different modes of operation exist at similar densities, discharge currents, and magnetic fields, depending on the history of formation of the high-density plasma. We expect to study the still unexplored region between the resistive arc regimes of RINGBOOG and the well-known classical high-density tokamak. Those types of discharges will operate in the impermeable regime. Furthermore, provisions will be made to control the current density and temperature profiles directly by skin heating.

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* E.P. Barbian, C.J. Barth, W. van den Boom, G.J. Boxman, J.J. Busser, W.J. Goedheer, C.A.J. Hugenholtz, L.C.J.M. de Kock, H.A. van der Laan, O.G. Kruyt, J. Lok, P. Manintveld, B.J.H. Meddens, L.Th.M. Ornstein, R.W. Polman, A. Ravestein, W.J. Schrader, F.C. Schüller, A.C.A. van Wees.

4. STOCKHOLM EXPERIMENTAL RESULTS

by

Stockholm Group, presented by B. Lehnert
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Impermeable plasmas with characteristic transverse dimensions of about 0.08 m have been confined in poloidal fields up to B = 0.8 tesla, at ion densities $n \simeq 2\times10^{21}$ m^{-3} and peak temperatures $T \simeq 2\times10^{5}$ K within the fully ionized core. The plasma body is separated from a surrounding neutral gas region of density $n_n \simeq 10^{21}$ m^{-3}, by a partially ionized boundary layer of thickness somewhat less than 0.01 m. The following main results have been achieved:

(i) The plasmas are generated and preheated by the crossed-field technique of rotating plasmas, which easily provides a burn-out power of several megawatts, to convert the filling gas into a fully ionized state.

(ii) This state can be further sustained, either by viscous shear heating in a rotating plasma, or by high-frequency magneto-acoustic heating in a non-rotating plasma. In both cases the fully ionized conditions can be preserved, down to a "minimum-power" level of about 0.5 MW, below which the plasma suddenly collapses into a lowly ionized gas.

(iii) During rotating plasma operation, Doppler shift measurements of impurity spectral lines, as well as probe recordings and studies of the equivalent electric capacity, give results being consistent with present models of the gas-blanket concept and its partially ionized boundary layer.

(iv) Free-wheeling times of about 200 microseconds and equivalent beta values up to 30% are observed in the rotating plasmas, and beta values at about 10% in the high-frequency heated non-rotating plasmas. All results indicate that the plasmas are at least stable with respect to the most important MHD-modes. This agrees with a previously performed stability analysis, in which the partially ionized boundary layer and the inhomogeneity of the confining magnetic field introduce important stabilizing mechanisms.

5.

GAS INJECTION INTO TOKAMAK DISCHARGES

by

Pulsator Team, presented by O. Klüber
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Due to pulsed gas inflow, the density of tokamak discharges can be increased by more than an order of magnitude. This results in appreciable improvements of the plasma parameters. In particular, the hydrogen ions constitute almost half of the plasma pressure and the energy confinement time increases roughly proportionate to the density.

The investigations on high density plasmas in the Pulsator device lead to the following conclusions:

1. the maximum density achieved so far is limited by the occurrence of the disruptive instability;
2. the penetration of hot neutrals into the plasma core appears to establish a source term sufficient to explain the observed densities. Thus, there is no need to assume additional mechanisms;
3. apart from the increase of the hydrogen content, the decrease of the effective ion charge is due to the decrease of the density of heavy impurities whereas the relative oxygen density does not change markedly.

It is discussed whether these conclusions hold also for the high density plasmas achieved in other machines.

6. TOROIDAL RESISTIVE DISCHARGES IN THE RINGBOOG FACILITY

The RINGBOOG-Team, presented by F.C. Schüller
Association Euratom-FOM, FOM-Instituut voor Plasmafysica,
Jutphaas, The Netherlands

A toroidal discharge with an impermeable gas blanket is studied in RINGBOOG: a tokamak-like device with $R_o = 0.52$ m, $r_o = 0.087$ m, $B_T \leq 3.2$ T, $\Delta\Phi = 1.2$ Vs, filling pressure p_o = 10 to 100 mtorr H_2. We report on discharges with $I \simeq 25$ kA at $B_T = 1.6$ T, V_ℓ = 300 to 400 V, pulse duration $\simeq 3$ ms. Radial profiles have been studied: $T_e(r)$, as measured by Thomson scattering, is in agreement with local conductivity temperatures ($Z_{eff} \simeq 1$) and is rather flat with $T_e(o) \simeq 3.0$ eV. Spectroscopically it is found: $T_i \simeq T_e$. As determined by CO_2-laser interferometry and confirmed by absolute Thomson-scattering intensities, $n_e(r)$ is hollow. At $p_o = 100$ mtorr, $n_e(o) = 2.5\times10^{21}$ m^{-3}, while $n_e(0.75\ r_o) = 5\times10^{21}$ m^{-3}. Combining these profiles we find a hollow pressure profile: $p(0.75\ r_o\ /p(o) = 1.4$.
This is in good agreement with magnetic probe measurements of B_T and B_p. At lower densities the pressure maximum shifts to the very outside: $r \simeq 0.9\ r_o$. The hollow profiles are explained by the reabsorption of Lyman-α radiation in the outer layers with high neutral density ($\ell_{abs} \simeq 1$ mm). This gives a strong overpopulation of $n \geq 2$ levels, leading to a local ionization rate for higher than predicted by Saha or Corona models.
A strong oscillatory (10 kHz) behaviour of many quantities is found. The spatial variation is a complex superposition of acoustic modes with $m=0$ and $n=0,1,2$ as most important mode numbers. The pressure oscillations in the outer regions correspond to the observed oscillations of B_T and B_p.
The low energy-replacement time, $\tau_E = 20$ μs, is due to line-radiation losses caused by the high neutral density. It is also found that there exists a specific relation between the neutral density of the gas blanket and the electron density in the cold plasma blanket. These observations together suggest that the application of a gas blanket for shielding hot tokamak discharges may be limited by the influence of radiation in the outer layers.

7. ESTIMATES FOR A POSSIBLE CRITERION ON WALL-RELEASED IMPURITIES

by

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Several methods are intended to reduce plasma-wall interaction and the resulting invasion of wall-released impurities into the hot plasma core to a tolerable level. In the following an attempt is made to quantify this aim somewhat by comparing the generation of wall material impurities with that of another and unavoidable type, i.e. the α-particles from fusion processes.

This comparison appears reasonable since, even without any kind of plasma-wall interaction, the burning cycle of a thermonuclear plasma eventually will be terminated by α-particle accumulation, unless we achieve a sufficient outward transport of these alphas and their disposal by some unloading mechanism, e.g. by a divertor or by a scrape-off limiter (1). However, even without sufficient outward transport of these alphas, the resulting pulse duration might not necessarily become too short for economic power production, although longer burning cycles or even genuine steady-state operation would be desirable.

8.

ON THE ACCUMULATION OF IMPURITIES AND HELIUM IN NEOCLASSICAL TOKAMAK REACTORS

by

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Classical transport in a hot plasma surrounded by a dense gas blanket leads naturally to steady-states with inverted plasma density profiles, which in addition to the gas blanket itself, screen the hot core from wall-generated impurities. However, source-free steady-states of a toroidal plasma, in which transport takes place according to neoclassical theory, do not possess inverted density profiles, so that in the absence of significant temperature gradients, impurities may accumulate at high concentration in the core.
The steady-states of a tokamak-like reactor are investigated on the basis of a simple model using a neoclassical transport theory, to determine the extent to which temperature gradients can prevent the build-up of heavy impurities in the central core and to determine the range of conditions under which steady-states exist, when the thermonuclear production of helium is taken into account. It is found that, at the moderately high values of charge state (e.g. 10) for which the transport theory employed will be valid, temperature gradient screening of impurities is fully effective at acceptably low contamination levels, ceasing to act only at very low concentrations. Helium-generating steady-states are found to exist above 10 keV, over a substantial range of helium concentration levels, with a mild degree of central 'peaking' becoming more marked only when the concentration is near the minimum level at which a steady-state exists.

9. APPLICATION OF THE COLLISIONAL TRANSPORT MODEL TO THE COLD-PLASMA BLANKET PROBLEM

by

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Steady states of magnetically confined plasma, without and with impurity content, are investigated in cylindrical and toroidal axisymmetric geometry. The classical transport model is adopted taking into account, in the toroidal case, the existence of the different regimes of neoclassical theory with inclusion of a generalization of the Pfirsch-Schlüter regime appearing at higher collisionality. Values of β for which the pinch effect is negligible are considered, and the aspect ratio is taken large. It is found that the steady-state solutions, indeed, show the appearance of a cool and dense blanket and that no important accumulation of impurities at the discharge centre occurs for them.

10. IMPURITY CONTROL BY MEANS OF A COOL PLASMA BLANKET*

A. Gibson[†] and M.L. Watkins[††]

A method is presented of controlling the influx of sputtered impurities into tokamaks. A cool plasma blanket (C.P.B.) is formed around the hot core of the discharge to prevent sputtering of wall material by both charged particles and charge-exchanged neutrals. Numerical simulations show that:

(a) the C.P.B. can be established and maintained by a low energy neutral beam;

(b) the C.P.B. is effective in preventing impurity contamination and

(c) the resulting clean plasma can be heated by a high energy neutral beam.

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[*] Work under EURATOM JET Design Contract/30-74-FUA-C. Papers to be presented at AGTOK Gas Blanket Workshop (Jutphaas, The Netherlands, 2-5 May 1977) and Eighth European Conference on Controlled Fusion and Plasma Physics (Prague, Czechoslovakia, 19-23 September 1977) and the authors' contribution to "The JET Project: Scientific and Technical Developments" - R8 (1976).

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[††] UKAEA, Culham Laboratory, Abingdon, Oxon, U.K. (Euratom/UKAEA Fusion Association).

11. PARAMETRIC CALCULATIONS CONCERNING THE INFLUENCE OF NEUTRAL INJECTION AND GASINLET ON IMPURITY TRANSPORT IN A TOKAMAK

by

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Impurity transport is one of the main problems in tokamak physics and of particular relevance for TEXTOR. Therefore the evolution of the impurity-profiles in space and time has been calculated with the Tokyo-version of Düchs' code taking into account neutral injection, the resulting enhancement of the plasma density and neutral gas influx from the outside. The beam deposition is computed from the data characterizing the beam cross-section and the beam trajectory. It is assumed that the flux of neutrals which arises from charge exchange of the deposited hot ions with the background neutrals penetrates the plasma without further charge exchange or ionization. This neutral flux is included in the recycled flux of cold neutrals.

The calculations concern 1. the reversion of the flux density of a light impurity (oxygen) by profile shaping thereby assuming that no heavy impurities are present and 2. the suppression of sputtering by the formation of a cool plasma blanket thereby neglecting the light impurities. The main results obtained are the following:

1. By applying weak gasinlet ($\dot{N} = 4.3 \cdot 10^{20}$/sec) the ion density maximum is shifted to the plasma edge and the impurity flux density (oxygen) is reverted in the vicinity of the plasma centre. By adding neutral injection heating with the beam axis shifted out of the equatorial plane the impurity flux density is reverted throughout the plasma except the region close to the plasma edge.
2. By applying strong gasinlet ($\dot{N} = 3.5 \cdot 10^{21}$/sec) the plasma edge is efficiently cooled (cool plasma blanket). The outflux of hot neutrals with temperatures above the sputtering threshold and therefore the influx of sputtered iron is almost stopped, if the beam power is less than about 1 MW.

12. SKIN HEATING IN RINGBOOG II

by

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The new RINGBOOG II will have special facilities to induce fast rising toroidal current pulses superimposed on both the resistive arcs of the RINGBOOG-type as well as on tokamak discharges. The rise time of the pulses is 3 μs with a flat top of approximately 15 μs. The pulses are programmable in time and in strength up to 50 kA.
The energy of these pulses will be deposited locally in the outer layers, due to the skin effect. Estimates obtained with the approach of De Kluiver, Piekaar*) and the numerical method of Kalfsbeek**) indicate in which density and temperature domains turbulence, and thus efficient absorption of energy will occur, and in which domain classical dissipation can be expected.
In some regimes a cold impermeable plasma blanket cannot be sustained by the available ohmic energy input. Oscillating currents in this layer may give sufficient additional heating. The influence of the additional heating pulses on the current density profiles on a longer time-scale will be investigated experimentally.

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*) H. de Kluiver, H.W. Piekaar, Rijnhuizen Report 73-82.

**) H.W. Kalfsbeek, private communication.

13. ON THE STABILITY OF BALLOONING MODES IN THE BOUNDARY LAYER OF A GAS INSULATED PLASMA

by

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In order to fulfill power density requirements in future steady-state fusion reactors the ion density in central parts must be of the order 10^{21} m^{-3}. In such systems high density neutral gas will surround the hot plasma, whether introduced on purpose or not, provided the neutral gas flux from the plasma is not continuously removed by external means. In these types of gas insulated plasmas large density and pressure gradients will arise close to the boundaries on account of plasma neutral gas interaction effects. In this paper the stability of gravitational driven ballooning modes in the boundary region is investigated. In particular, the coupling between plasma and neutral gas investigated in previous stability analysis is reconsidered. Also effects previously neglected for example the Nernst effect is taken into account.

14. HIGH-β TOKAMAK EQUILIBRIUM AND STABILITY CONSIDERATIONS

by

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The results of recent work on sharp-boundary high-β tokamaks in collaboration with D'Ippolito, Freidberg, and Rem are brought to bear on gas-blanket confinement schemes. Here, the main effect of the gas blanket is thought to provide cooling of the exterior region resulting in a finite conductivity of the force-free layer surrounding the hot ideally conducting plasma core. Scaling laws for high-density tokamak equilibrium and stability are derived exhibiting separately the influence of non-circular cross-sections on the equilibrium and the influence of the current density profile on global MHD-stability. The relationship with flux-conserving tokamaks is pointed out.

15.

NUMERICAL MODELLING OF HIGH-DENSITY PLASMAS IN TOKAMAKS WITH PULSED GAS INFLUX

by

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Plasma transport in tokamaks is based both on processes in the plasma volume and on processes on the boundary. For the neutral hydrogen (density n_o, velocity v_o) the Düchs-Code takes into account ionization, charge exchange, linear isotropic propagation in the volume and a given neutral flux specifying the boundary condition. Numerical modelling of standard tokamak operation with small additional gas influx worked very well, when a v_o corresponding to a few Frank-Condon eV was assumed and when n_o was determined from a recycling condition with an additional source term. For pulsed gas influx (as in Pulsator or Alcator), however, this model leads to hollow plasma density profiles which shield all further incoming neutrals and limit the plasma density on axis to values not above 10^{14} cm^{-3}. Instead of postulating an enhanced diffusion, that cannot easily be motivated, the Düchs-Code prevents hollow profiles by altering the theory for the boundary conditions. Measurements on Pulsator and Alcator could be reproduced in detail when $v_o = \sqrt{2kT_i/m_i}$ was assumed.

In order to justify this assumption, the back-scattering of particles from the wall was studied in more detail. By taking into account a spectrum of velocities for the incoming particles (ions, neutrals) and by determining the portion of particles being reflected or absorbed on the basis of recently measured coefficients, outward peaking of the plasma density was avoided. The additional cold gas enters the plasma volume - as previously - with a few eV. It is not claimed that the described boundary conditions are the only way to model high density tokamaks. An additional anomalous transport in that regime might exist.

VELOCITY DISTRIBUTION OF NEUTRALS

by

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The velocity distribution of neutrals emitted by tokamak plasmas are analyzed by means of a detailed kinetic description including neutral particle - wall interaction. It is shown that the prominent processes between plasma and neutrals are ionization by electron impact and charge transfer. The solution of the kinetic equation leads to the result that the high energetic tail of the energy distribution of neutrals is dominated by the temperature of ions originated in the centre of the tokamak, whilst the low energy part is influenced by different processes at the wall and inside the wall sheath. Evaluating the central ion temperature it must be taken into account that at least the energy spectrum has to be measured up to a maximum energy of approximately 5 times the central ion temperature. For comparison, neutral energy spectra and ion temperatures in the tokamak discharges T3, Pulsator, TFR and Textor are computed. Additionally, measurements of neutral particles distribution functions in the low energy range using a high current, low pressure arc are reported.

17. ANOMALOUS TRANSPORT OF COLD PLASMA AND IMPURITIES

by

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a) By bleeding neutral gas into the discharge recent tokamak experiments have reached a density regime where the plasma becomes "optically" thick for neutral penetration. We explore the possibility that collective modes can produce the transport of cold plasma from the edge of the column towards the centre. The relevant modes are unstable if the temperature gradients become sufficiently steep with respect to the density gradient.

b) The transport of particles and thermal energy that can result from plasma modes driven by a relatively small concentration of impurities is discussed. In the short mean free path limit fluid modes exist associated with the finite ion thermal conductivity. In the long mean free path limit kinetic modes appear that are destabilized by inverse ion Landau damping. These modes may be unstable for an impurity density distribution peaked toward the inside of the plasma, for realistic main ion temperature gradients, and can transport impurities and thermal energy outward.

18. THE ENERGY BALANCE OF A STEADY-STATE INFINITELY LONG CYLINDRICAL DISCHARGE IN HYDROGEN GAS

by

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Numerical calculations of steady-state temperature and pressure profiles are presented for an infinitely long cylindrical discharge in hydrogen gas. The discharge is heated by an axial current I_z and the energy is lost by thermal conduction, by diffusion and by the emission of radiation. The Ly_α-radiation, emitted in the centre of the discharge, is reabsorbed in the cool outer layers, where the neutral density is high. An axial magnetic field, B_z, reduces the thermal conduction and provides a pressure gradient due to the ambipolar diffusion$^{1)}$ and the Nernst-Ettinghausen effect$^{2)}$.
The calculation of the neutral density is based on a simplified level scheme of the hydrogen atom. In this scheme we distinguish three discrete levels, viz. the ground state and the first two excited levels; all higher levels are lumped into a band with average transition probabilities. In this level scheme we have also accounted for the diffusion of groundstate atoms.

Results are presented for discharges with temperatures on the axis up to 5 eV and maximum electron densities between 5×10^{20} m^{-3} and 1.5×10^{21} m^{-3}. The results show, that in spite of the strong reabsorption of the Ly_α-line at high densities, the other line radiation is the most important energy loss in the outer regions. Furthermore, it is found that the influence of the wall is limited to a region very close to that wall; this is due to the impermeability of the discharge.
Comparison of the results of this cylindrical code with the profiles of the RINGBOOG experiment shows similarities, for instance the temperature pr[illegible]s flat and the electron density stays high near the wall. However, the neutral density in the cylindrical model is far too low, while also the dissipated energy is far below the RINGBOOG values. In order to simulate toroidal effects with enhanced electron diffusion, we have repeated the calculation with a 15 times increased flux of electrons. The results of this calculation will also be presented.

References

1) Wienecke, R., Z. Naturforsch. 18a (1963) 1151.
2) Klüber, O., Z. Naturforsch. 22a (1967) 1599.
3) The RINGBOOG-Team, presented by F.C. Schüller, Int. Symposium on Plasma Wall Interaction, Jülich, 1976, paper E8.

19.

BETA LIMITS FOR HIGH-DENSITY TOKAMAKS DUE TO NEOCLASSICAL ION-HEAT CONDUCTION

by

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The energy confinement of high density tokamak discharges in Alcator is evaluated by means of a simple model. It is assumed that electron temperature and pressure profiles as found experimentally by means of Thomson scattering can be approximated by gaussians. It will be shown that the ion temperature must be very close to the electron tempeture. Under the assumption that Z_{eff} is constant over the radius ($j \propto T_e^{3/2}$) the effective heat flow is calculated and compared with the heat flow predicted by the neoclassical heat conduction of the plateau and Pfirsch-Schlüter regimes.

As a result it is found that the effective heat flow in the central core can be explained by neoclassical ion heat conduction alone. In the outside layers the contributions of convection, charge-exchange losses and impurity radiation become of equal importance as the (Pfirsch-Schlüter) ion heat conduction.

Several conclusions can be drawn:

1) Anomalous electron heat conductivity is not important in high density tokamaks.
2) β_θ is limited by neoclassical heat conduction. Scaling laws will be given.
3) The $\beta_{\theta e}$-limit becomes higher with the ionic charge number if other gases than hydrogen are used.

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20.

SPECIFIC DIAGNOSTICS FOR COLD BLANKETS

by

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Observations to be done in the cold plasma blanket region should provide a link between the region of the plasma-wall interaction and of the central plasma core. The expected strong gradients impose specific demands on the diagnostics: measurements must cover changes of several orders of magnitude and permit an overlap between methods of different kind. The time evolution of the parameters becomes especially important if correlations between evolving instabilities and the properties of the gas blanket are studied.

Methods promising to yield the needed spatial resolution are preferentially based on non-material probing, either by laser light or by particle beams.

The possibilities to extend Thomson scattering towards an instant recording of the density and temperature profiles along the traversing laser path are discussed.

The heavy ion-beam probe might become an additional method useful to determine the space potential.

To obtain impurity concentrations and the neutral density distribution the resonant or near-resonant Rayleigh scattering is considered to become an important diagnostic.

21.

NEAR RESONANCE RAYLEIGH SCATTERING

by

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Resonance scattering is a well-known means to detect low densities of neutral atoms, also suited for plasma diagnostics. In certain cases, however, Rayleigh scattering in the close neighbourhood of a resonance may be the better method.

The limitations of resonance scattering, namely optical thickness, equal population of energy levels, background radiation, will be discussed and compared with the case of Rayleigh scattering.

A formula for the cross-section which covers Rayleigh as well as resonance scattering, derived by Mollow for the case of high incident electromagnetic fields will be used for more detailed discussion.

22. DETECTION OF NEUTRAL HYDROGEN AND LIGHT IMPURITIES BY RESONANCE SCATTERING IN THE VACUUM ULTRAVIOLET

by

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By resonance scattering in the vacuum ultraviolet, the densities of several gases, especially atomic hydrogen, can be determined space-resolved without a knowledge of the electron densities and temperatures. To detect low densities in the order of 10^{10} cm^{-3}, as expected in tokamaks, powerful light sources are required.
Experiments have been carried out using a capillary discharge in helium with a blackbody temperature of about $5 \cdot 10^4$ K, a duration of 2 μs and a diameter of 0.2 cm. It was shown that krypton and deuterium at densities below 10^{10} cm^{-3} could well be measured.
Estimates of the sensitivity are given for other gases. The applicability of the fluorescence spectroscopy for the detection of atomic hydrogen and impurities in the shadow of the limiter and in the divertor chamber will be discussed.

23. VELOCITY ANALYSIS OF SLOW NEUTRALS

by

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The velocity analysis of neutrals which escape from the plasma is traditionally achieved by energy analysis of ions resulting from stripping the neutrals in a stripping cell. Advantages of this method are a high detection efficiency and an easy velocity analysis of the resulting ions with the relatively simple electrostatic analysis.

The main disadvantage is that the method cannot be used for analysis of neutrals with velocities smaller than 150 eV as the stripping process shows a thresholdlike behaviour in this energy range.

For low temperature plasmas or for analysis of the cold plasma at the wall other methods have to be used.

A second disadvantage of the stripping method is that, in particular for low temperature plasma, only the tail of the ion velocity distribution is measured. Thus, care must be taken that a non-thermal tail is misinterpreted as part of a thermal distribution.

In Eindhoven the different approach of velocity analysis of (slow) neutrals by time of flight (TOF) method is used to obtain the velocity distribution of the ions in full detail including the low velocity part1). In this method the slow neutrals are also detected (even preferentially, contrary to the stripping technique). The price to be paid is the smaller sensitivity and a more difficult discrimination between background neutrals and plasma neutrals. In continuous arcs (as in Eindhoven) this can be overcome by time integration. In pulsed systems an effective discrimination of plasma- and background neutrals is essential in regard to the limited integration time. For high-density tokamaks the method should be applicable with careful optimalization of the detection efficiency the use of UHV techniques and maximizing the neutral beam intensity. Then full advantage can be taken of the potentials of the method: full detail of the velocity dependence of the escaping *slow* neutrals. The TOF method should be regarded as a complementary diagnostic method different from the stripping method and applicable under different conditions (i.e. low temperature and high density).

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1) P.G.A. Theuws, H.C.W. Beijerinck, D.C. Schram, and N.F. Verster, J. Appl. Phys. May 1977 in press.

24.

FT-EXPERIMENTS

by

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The FT-tokamak has been constructed to perform experiments on the physical behaviour of a plasma in the high density, high-current density regimes, which were expected to be reached in high toroidal field devices. In this paper the main technical features of the design will be recalled and the expected machine performances in different modes of operation will be listed. The characteristics of the diagnostic apparatuses being installed on the machine or under preparation will be described and an outline of the planning of the experimental programme will be given.

25. THE EXPERIMENTAL PROGRAMME OF RINGBOOG II

by

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A description will be given of the RINGBOOG II experimental facility. In this tokamak-like device ($B_T \leq 3$ T, $\Delta\Phi = 1.2$ Vs, $R = 0.56$ m, $a = 0.08$ m) resistive arcs of the RINGBOOG-type as well as tokamak discharges can be produced. RINGBOOG II has an improved vacuum vessel of stainless steel bellows, four ceramic breaks, and a copper shell. The breaks allow for the penetration of fast rising current pulses for additional heating; the copper shell acts as the primary winding.
In RINGBOOG discharges (typical $T_e \sim 2.5$ eV; $n_e \sim 8\times10^{20}$ m^{-3}; $I_p \sim 25$ kA) we will study possible changes in discharge parameters due to the new stainless-steel wall and the stabilizing effect of the copper shell. Better vacuum conditions will hopefully enable us to explore a regime of filling pressures of several 10^{-3} torr, i.e. in the parameter range between the resistive arcs and tokamaks with pulsed gas feed. Electron densities of a few 10^{20} m^{-3} are expected.
In a later stage also tokamak discharges with pulsed gas feed can be produced. On a relatively long time-scale (> 100 ms) the stabilizing function of the copper shell is lost. Then, the stability of the equilibrium position of the plasma torus in the horizontal plane is strongly affected due to the close proximity of the central core of the transformer. This imposes severe requirements on the vertical field configuration. A stable configuration has been found which even covers the change of β_p from 0.2 to 2.
In all types of discharges additional toroidal current pulses can be induced on a short time-scale for local additional heating. Studies will be conducted on the influence on the current density profile on a longer time-scale and also on the possibility to sustain a cold plasma blanket by means of skin heating.

26. INVESTIGATING A COLD BLANKET IN TEXTOR

by

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Possible applications of the TEXTOR device for investigating a cold blanket are described. TEXTOR is specially designed for observing the limb of the plasma, the limiter zones adjacent to the plasma boundary, and the walls facing the plasma. Neutral injectors and bundle divertors are foreseen to bias the temperature in the outer region of the plasma core.

According to the present design flow rates of cold neutral gas and the distribution of gas influx along the "surface" of the plasma are feedback controlled. Methods are described how to seed cold gas homogeneously distributed at a low flux density and how locally for obtaining a high flux density. The latter one should be good enough to isolate the plasma for a time of about 10 msec from material walls. An investigation of the plasma during this time could have some relevance to high density gas blanket research, if the plasma will remain MHD-stable.