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ABSTRACT

Facing the year 2000, some proposals for a balanced strategy of fusion research are given in this paper. Fusion research by the world community has made substantial progress, and it is now possible to build an experimental test reactor based on the tokamak confinement principle, in the form of a global commitment such as the ITER/NET project. Nevertheless further investigations are needed before the practical use of fusion energy becomes a reality. With regard to this, and to the time gap formed by the planning and construction period of ITER/NET, continued activities have to take place at the national laboratories, to preserve the quality of plasma physical research and the competence of fusion scientists and engineers, as well as to guarantee research on alternative lines aiming at an improved reactor concept.

Some aspects are given in this context on the desired properties of an optimal fusion reactor, including a high plasma beta value, a minimized imposed toroidal magnetic field, controlled or non-existent disruptions, steady-state operation, minimized plasma-wall interaction, and the absence both of a stabilizing conducting wall and of active feedback systems.

1. Introduction

Research on controlled thermonuclear fusion by the world community has made substantial progress during the last decades and is now facing a new period, the strategy of which has to be examined. In this context some aspects will be given on the present state and future prospects of research, and on associated questions concerning alternative lines of closed toroidal magnetic confinement. Part of the discussion will be focussed on a number of improvements which appear to be necessary for magnetic confinement to result in a practical use of fusion energy.

2. Present State and Future Prospects of Fusion Research

Currently conducted large tokamak experiments, and in particular JET, are at this point close to breakeven, as defined by a marginal balance between produced fusion power and power losses. An important milestone in fusion research has thereby been passed, and it is now within reach to study tokamak plasmas under reactor relevant experimental conditions. The next step is to demonstrate controlled ignition and extended burn of DT plasmas, as well as to demonstrate and perform integrated testing of components required to utilize fusion power for practical purposes [1]. Such a step does on the other hand not have to fulfill all criteria of economical and technical reactor feasibility. It should mainly provide the possibility of studying reactor components on full scale, before an optimal and commercial reactor has been realized. Within this frame the ITER/NET project becomes an approach of great importance.

The time schedule for ITER/NET comprises an extensive work on planning and construction during the next two decades. Within this perspective three points are made here which have to be taken into account in the future strategy of fusion research:

- The planning and construction period of ITER/NET forms a time gap in the experimental activities.

For the fusion research programme not to lose momentum and qualified manpower, this gap has to be filled by continued plasma physical activities at the national laboratories and universities. The aims of these activities would be both to support a continued plasma physical research of high quality, and to educate and preserve a staff of qualified scientists and engineers. The costs for this can be kept at a moderate level, as compared to those of the large scale international projects.

- So far the progress of fusion research has not relied solely on results from large scale projects. There are several examples on small and intermediate scale experiments in which results of decisive importance have been achieved.

- With all respects to the excellent performance of JET and other large tokamak projects, further research and development are required before the practical use of fusion energy becomes a reality. It is at this stage not certain which type or types of confinement schemes will be able to satisfy the various requirements of a commercial reactor in an optimal way. It is therefore justified to continue the research on improvements, alternative lines and new ideas. The final goal consists of the best possible reactor, from technical, economical and environmental points of view.

For the moment the world resources for fusion research are limited and seem to become reduced in the nearest future. On the other hand, future limited possibilities of covering the global energy needs may change this situation into that of an increased research effort. Facing the year 2000, a balanced strategy is here proposed to consist of the following measures:

- A global effort to tackle the fusion technological problems in terms of the common tokamak project ITER/NET.

- National efforts which support ITER/NET but also include continued activities at the home basis. These activities should preserve the quality of plasma physical research and the competence of fusion scientists and engineers, and should include efficient research on alternative lines aiming at an improved reactor concept.

3. On an Improved Reactor Concept

A reactor for practical and competitive power production comprises a number of desired improvements and unanswered questions to be touched upon in this section.

3.1. Some Desired Physical and Technological Properties

Among the desired physical and technological properties of an optimal fusion reactor the present paper concentrates on those being listed in Table 1 and discussed in the following paragraphs.Further research is necessary to find out whether part or all of these and other desirable properties can become a reality in one and the same confinement system. The points made in this section should therefore also be taken as proposals for such a research.

3.1.1. The Plasma Beta Value

For a deuterium-tritium plasma of average ion density n and temperature T a plasma beta value $\beta = 4\mu_o nkT/B^2$ is defined, where B stands for the spatial square mean value of the total magnetic field strength. With a total thermonuclear power P being produced within a toroidal plasma volume V having the minor radius $\bar{a}$, the corresponding power density becomes [2,3]

$$P/V = 2\Pi/\bar{a} = F\beta^2B^4 \propto F(nT)^2 \qquad (1)$$

where Π is the total wall load. The function F is nearly constant within the temperature range of reactor interest.

The simple relation (1) has a number of important consequences which demonstrate the advantages of a high beta value, provided that such a value can be reached under stable plasma conditions and with acceptable losses due to plasma transport:

- For a fixed magnetic field strength B being limited by technical constraints the power density increases strongly with beta which parameter thus promotes compactness of the fusion reactor.
- For a fixed power density, a high beta value permits a low field strength B which leads to reduced coil stresses and coil power losses. In some cases this could remove the technical complication of superconducting coils. The cyclotron radiation losses also become reduced by a high beta. An incomplete plasma reabsorption of such losses deteriorates the heat balance of a low-beta plasma, but is expected to be of minor importance at high beta values [4]. Moreover, a reduction of the total field strength B does not necessarily enhance the plasma transport in a critical way. Thus, a

reduced or non-existing toroidal component B_ϕ still leads to acceptable losses by plasma transport when B_ϕ has a comparatively weak effect on the plasma confinement and transport, as compared to the effects of a poloidal magnetic field component B_θ.

- Even if the wall load Π turns out to be limited by material constraints, a high beta value becomes advantageous for the same reasons as those just being mentioned. Certainly a realistic plasma radius $\bar{a}$ and a limited wall load also limit the DT reactor to beta values of a few percent in schemes which require a strong toroidal magnetic field [3]. However, this neither applies to schemes which for a given plasma pressure can be operated at a lower total field strength B, nor to the advanced fuel reactions. Consequently a limited wall load does not weaken the arguments for aiming at a high beta value

- As compared to its value for the DT-reaction, the function F becomes smaller in the case of advanced fuels. At a given value of B the power density and power to loss ratio can then be kept at reactor relevant levels, provided that sufficiently high beta values can be reached [3].

- The beta value also becomes connected with the externally imposed toroidal field and the plasma boundary conditions as discussed in the following Sections 3.1.2 and 3.1.4.

It has finally to be remembered that disruptions represent a serious technical problem in certain full-scale reactor schemes, especially at high beta values for which there is a substantial amount of magnetic energy which can be released. In particular, this can become a limitation of tokamak schemes where attempts are made to increase the beta value by means of an elongated cross section, thereby relying upon active feedback control of vertical displacements. If possible, the best and alternative way would of course be to find a scheme for which disruptions do not exist.

3.1.2. The Externally Imposed Toroidal Magnetic Field

Provided that a stable plasma confinement can be realized, a reduction or even removal of the externally imposed toroidal magnetic field B_ϕ has a number of advantages. So far there is no proof for fusion relevant confinement systems not to exist under such conditions. The advantages of toroidal field minimization can be summarized as follows:

- The pressure gradient in quasi-steady MHD equilibrium is mainly balanced by the force due to the poloidal part of the confining magnetic field,in cases where there is no steady state mechanism which is able to drive strong poloidal plasma currents. This holds true also in the cases of anisotropic and/or anomalous resistivity and when the Nernst effect has to be taken into account. The toroidal component of the magnetic field contributes poorly to the confinement, except in pulsed systems such as the theta pinch. In tokamaks a strong toroidal field becomes necessary for reaching high toroidal plasma currents, on account of the Kruskal-Shafranov limit. However, this limitation does not necessarily become a constraint in other types of confinement system.

- Enhanced beta values can be obtained by minimizing B_ϕ.

- A minimized or even fully removed toroidal field simplifies the technical coil construction.

3.1.3. Steady State Operation

Steady state operation of the fusion reactor is highly desirable, but only under the subsidiary condition of a minimized circulating power which guarantees an acceptable efficiency of the total power balance. In tokamaks the current drive by auxiliary means, such as by externally imposed high-frequency fields, has made substantial progress. Notwithstanding this there are problems when attempts are made to reach reactor relevant particle densities under the condition of an acceptable amount of auxiliary power for current-drive.

Promising intrinsic mechanisms in the plasma which do not involve additional amounts of auxiliary power are those of the bootstrap and diffusion driven bootstrap-like [4] effects. Large bootstrap-like currents can be obtained within the major part of the plasma volume, in particular at high plasma beta values for which the poloidal magnetic field component becomes appreciable. Within the frame of MHD theory, current drive by this mechanism becomes questionable near the poloidal field singularity at the magnetic axis. However, this is the case only for a small fraction of the plasma volume within which other current-drive mechanisms could be applied at the expense of a small additional power input only. There is also a possibility that kinetic particle orbit effects could contribute to the bootstrap-like mechanism at the magnetic axis.

Technical simplicity is gained by the use of non-superconducting coils, at the expense of an increased circulating power. The disadvantage of this is minimized by a high beta value.

3.1.4. The Plasma Boundary Region

The physical conditions of the plasma boundary region are of vital importance to the equilibrium and stability of the entire plasma body. There are two concepts which deserve special attention in this connection:

- The magnetic limiter (divertor) does not only provide a control and reduction of plasma-wall interaction but also has an impact on the plasma profiles, thereby affecting the plasma boundary and stability conditions.

- In tokamaks it has become possible to reduce the plasma-wall interaction by means of impurities which decrease the plasma temperature in a radiative boundary layer. Alternatively, and under purified plasma conditions, a cold gas mantle can also provide means for control and reduction of plasma-wall interaction, and for affecting the plasma profiles, equilibrium and stability. Moreover, a combination of the divertor and cold-mantle concepts does not only appear to be possible, but should also establish itself per se within certain parameter ranges, as determined by the quasi-steady plasma-neutral gas balance. Earlier investigations on this balance indicate that a fully developed cold-mantle, defined by a dense and cool neutral gas region being separated from a hot plasma core by a partially ionized boundary layer, can only exist at sufficiently high beta values and not in present tokamaks [4]. Thus, the cold-mantle concept could become subject of a renewed interest to future reactor schemes operating at increased beta values.

3.1.5. A Conducting Wall and Active Feedback Systems

In a number of confinement systems a conducting wall has to be located close to the plasma to improve MHD stability, often in combination with active systems for feedback control. If other means of complementary MHD stabilization can be found, this would facilitate the technological problems.

3.2. Insufficiently Explored Areas of Theoretical Research

There are a number of unanswered questions and incomplete theoretical models in fusion plasma theory. The outcome of further research and the understanding of so far unclear points may very well turn out to have an essential impact on a further development of the fusion reactor. In addition to the large number of commonly discussed problems, two questions for further research will be raised here, one in MHD theory and one in kinetic theory.

3.2.1. Electromagnetically Induced Surface Currents

The first question concerns magnetic confinement schemes in which the externally imposed magnetic field has a considerable spatial inhomogeneity within the plasma confinement volume. For a large class of plasma perturbations, electromagnetically induced surface current phenomena should then arise on account of the field inhomogeneity, thereby affecting macroscopic plasma stability. To the author's knowledge these phenomena and their rôle in MHD stability theory have not been sufficiently explored. They are not expected to become important in the case of the comparatively weak magnetic field gradients in tokamaks, but cannot be neglected in schemes such as Extrap [4].

3.2.2. Large Larmor Radius Effects

The second question concerns the kinetic large ion Larmor radius (LLR) effects which arise at high beta values. The number θ_i of average ion Larmor radii $\bar{a}_i = (2m_i kT/e^2B^2)^{1/2}$ contained within the minor plasma radius $\bar{a}$ at a total toroidal plasma current J_ϕ and a temperature T_o at the magnetic axis is approximately given by [4]

$$\theta_i = \int_o^{\bar{a}} (dr/\bar{a}_i) \simeq c_o(B/B_\theta)J_\phi/T_o^{1/2} \simeq k_o(N/\beta)^{1/2} \qquad (2)$$

Here B_θ is the square mean of the poloidal magnetic field strength, $B^2 = B_\phi^2+B_\theta^2$, N is the plasma line density, $c_o = 0.094\ K^{1/2}/A$, $k_o = 1.6\times10^{9}\,m$, and SI units are used for a deuterium-tritium mixture.

We now consider a disturbance having the specific wave length λ, thus varying in space at a given time t from zero to its full amplitude within the distance $\lambda/4$. On the average an ion sweeps across the distance $2\bar{a}_i$ during a gyro period. Within this distance the perturbation changes in space by a fraction f_i of its amplitude. A rigorous MHD description of the dynamics of the disturbance then requires the fraction f_i to be much smaller than unity. For $f_i \gtrsim 0.5$, i.e. when $2\bar{a}_i \gtrsim \lambda/8$, kinetic effects should therefore have an appreciable influence on the dynamic behaviour of the disturbance. The corresponding critical minimum wave length becomes [4]

$$\lambda_{LLR} = k_{LLR}\bar{a}/\theta_i \qquad (k_{LLR} \simeq 16) \qquad (3)$$

Further, for any plasma disturbance which can be expanded into a spectrum of wave lengths λ, the part $\lambda \lesssim \lambda_{LLR}$ of the spectrum thus has to be treated in terms of kinetic theory.

If this turns out to be the case for a substantial part of the spectrum, i.e. when λ_{LLR} does not become negligible as compared to the minor radius $\bar{a}$, then MHD-theory gives a poor and even incorrect picture of plasma dynamics.

As indicated by eqs. (2) and (3) the currently discussed LLR effect becomes particularly important in high-beta systems. There it is expected to introduce kinetic phase-mixing effects. Such effects will also appear in a strongly inhomogeneous magnetic field, on account of the thermal dispersion of the particle guiding centre drifts [4]. The kinetic phase mixing by these drifts becomes important for wave lengths of a density perturbation which are comparable to or smaller than a critical minimum length λ_{GCD} where

$$\lambda_{GCD}/\bar{a} \simeq 2\pi^2 a/L_B\theta_i \qquad (4)$$

Here $L_B = B/|\underline{\nabla}B|$ stands for the characteristic length of the magnetic field inhomogeneity.

As a final illustration of relations (2) and (3) three examples are mentioned here:

- Recently given data on ITER yield $\lambda_{LLR}/\bar{a} \simeq 0.03 \ll 1$. In this case MHD theory becomes a good approximation.

- For the second stability regime of tokamaks a recent investigation [5] is taken as an example where there is a medium sized experiment with major radius R=1.5 m and B =1 T. For an aspect ratio $R/\bar{a}=4$ and a plasma temperature $T_o=10^7$K the ratio $\lambda_{LLR}/\bar{a}$ then becomes about 0.3. This implies that there is a considerable influence from kinetic effects.

- An extrapolation of Extrap to the reactor parameter range with $T_o = 3 \times 10^8$ K and $J_\phi = 10^7$ A likewise results in $\lambda_{LLR}/\bar{a} \simeq 0.3$, and thus in considerable deviations from a pure MHD behaviour.

4. On Alternative Lines of Toroidal Magnetic Confinement

There are a number of alternative magnetic confinement systems which possess specific potential advantages over the tokamak and which could contribute to the development of the full potential of fusion [1]. Among these the following can be mentioned:

- The principles of optimization of the Advanced Stellerator [6] include a high quality of vacuum field magnetic surfaces, good MHD stability and neoclassical transport properties without disruptions, and the ability of non-inductive steady-state operation.

- The Reversed Field Pinch (RFP) makes the parameter region of low satefy factors accessible. The toroidal field reversal results in high magnetic shear so that stability becomes possible at relatively high beta values [7].

- The Extrap scheme consists of a Z-pinch immersed in an octupole field, with a weak or non-existing toroidal magnetic field [4]. It can be considered as an extension and modification of the tokamak and stellarator to higher beta and lower safety factors, of the stellarator to strongly enhanced gradients and shear of the externally imposed magnetic field, and of the RFP to increased beta values, in presence of a magnetic limiter and possibly in absence of a conducting wall. Preliminary results indicate that this leads to a suppression of the Taylor dynamo mechanism by the octupole field. Research on Extrap is still at an early stage, but it is the hope that this scheme should be able to better satisfy the properties listed in Table 1.

5. Conclusions

The present discussion can be summarized as follows:

- Fusion research has made substantial progress during the last decades. It should now become possible to build an experimental test reactor based on the tokamak confinement scheme, in the form of a global commitment such as the ITER project.

- In coordination with this commitment, continued activities have to take place at the home basis of the national laboratories. These activities should both preserve the quality of plasma physical research and the competence of fusion scientists and engineers, and guarantee an efficient research on alternative lines which aim at an improved reactor concept.

- The desired properties of an optimal fusion reactor comprise a high plasma beta value, a minimized imposed toroidal magnetic field, controlled or non-existent disruptions, steady-state operation, minimized plasma-wall interaction, and the absence both of a stabilizing conducting wall and of an active feedback system.

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Table 1. Some desired properties of an optimal fusion reactor.

Properties	Related Questions
High plasma beta value	- Promotes a high power density whenever this becomes necessary. - Promotes a high fusion power to loss ratio. - Minimizes coil stresses, coil power loss ratio, and cyclotron radiation loss. - Becomes a condition for the future use of advanced fuels. - Advantageous also in case of limited wall load.
Minimized toroidal magnetic field	- In quasi-steady equilibrium the plasma pressure is mainly balanced by the force from the poloidal magnetic field. - Enhanced beta values are obtained. - The technical construction is simplified.
Controlled disruptions	- Necessary for operation of full-scale reactor. - More critical for elongated cross-sections which aim at an increased beta in tokamaks.
Steady state operation	- Desirable under the subsidiary condition of a minimized circulating power. - Bootstrap current provides one possibility for current drive within main part of plasma volume; is reinforced at high plasma beta values.
Minimized plasma-wall interaction	- Magnetic limiter (divertor) and cold gas mantle provide means of controlling plasma-wall interaction, and affect plasma profiles, equilibrium and stability. - Cold-mantle becomes fully developed only at sufficiently high beta values. Can be combined with divertor.
Removal of conducting wall and active feedback systems	- Simplifies technology.

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Key words: Fusion research, future prospects, magnetic confinement, alternative lines.