Expanded Boundary with Destroyed Flux Surfaces

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ABSTRACT

It is proposed to expand the outermost flux surfaces in tokamaks to divert the heat flux emerging from the plasma core. The approach previously discussed in detail is to deform the poloidal field configuration for expansion of the boundary. A simpler approach is discussed here which does not require any coil system or power supply, an attractive feature for reactor application.

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1. INTRODUCTION

Impurity and heat removal problems are major concerns in designing a reactor-grade tokamak such as ETF. The ultimate solution of these problems for a tokamak reactor would satisfy a whole set of requirements:

1. Distribution of the heat flux emerging from the plasma core over a large surface area.
2. Reduction of impurity generation to an acceptable level.
3. Removal of impurities (especially thermal alpha particles) from the system.
4. Compatibility with reactor engineering requirements.

The concepts developed previously, such as poloidal divertor, bundle divertor and large surface limiter, are likely to fail to satisfy these requirements simultaneously.

Requirements (1) and (2) can be satisfied if the heat from the plasma core is converted into radiative power at the boundary, provided that impurity radiation does not dominate the energy loss in the plasma core. Unfortunately, the greatly increased heat flow in future reactor-grade tokamaks renders natural impurity edge cooling improbable; in fact, an order of magnitude enhancement of the radiative power at the boundary is required.

A new edge cooling scheme is proposed which modifies the poloidal magnetic configuration to provide a large radiative cooling volume (Ref. 1). An example of such a modified plasma configuration is illustrated in Fig. 1, where one sees that the top outermost flux surfaces are expanded, resulting in a significant increase in the boundary volume. This approach has the virtue that, even without enhanced radiative power, the heat flux is diverted over a large surface area, thus satisfying requirement (1).

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Fig. 1. The proposed expanded boundary approach

For the expanded boundary approach, the radiative power in the boundary is obviously enhanced by a large boundary volume. The electron density and impurity concentration in the boundary are also increased by various transport effects which are specific to this configuration, thus enhancing the boundary radiative power. Therefore, effective radiative cooling may be realized, resulting in very low limiter temperature and consequently minimization of impurity generation [requirement (2)].

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Once the heat flow is decoupled from the particle flow, as is the case in this scheme, alpha particle pumping becomes a relatively easy matter. Furthermore, natural plasma flow near the wall helps to enhance pumping of alpha particles significantly, eliminating the ash removal problem [requirement (3)].

The MHD configuration of the expanded boundary can be obtained even if the coils are located far away from the plasma, i.e. outside the toroidal coil system, as is depicted in Fig. 2. (Stabilizing or feed-back coils, which are simple copper coils located close to the plasma, are needed to shape the plasma accurately. This is true even for a circular tokamak plasma.) The required coil current is modest compared with the conventional poloidal divertor design [requirement (4)].

Fig. 2. A expanded boundary configuration for ETF type tokamak

The numbers labeling each coil represent the current passing through the coil in unit of megamperes

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2. EXPANDED BOUNDARY WITH DESTROYED FLUX SURFACES

It is not essential for the boundary magnetic surfaces to be closed; all that is required is that there be a large volume of low temperature plasma through which power flows from the core. This suggests an alternative means of implementing the expanded boundary scheme. By applying a non-axisymmetric field, the magnetic surfaces of the outer part of the plasma column are destroyed, resulting in expansion of the outermost flux surfaces. It is well known that even very weak helical magnetic fields (and hence a modest current in the external coil) can generate magnetic islands; overlapping of such islands leads to a stochastic structure of the field line, as illustrated in Fig. 3 (Ref. 2). Numerical study of the field topology of this configuration is now underway. As to utilizing a helical field, F. Karger and K. Lackner have proposed a helical divertor (Ref. 3). T. Tazima and M. Sugihara have proposed an improved version in which helical resonant islands rotate to divert the heat flux (Ref. 4). The concept discussed here has more attractive features (Ref. 1).

Fig. 3. Expanded boundary with destroyed flux surfaces

The expanded boundary approach with destroyed flux surface functions in almost the same fashion as the one utilizing deformation of the poloidal configuration. A stochastic field line structure provides a very high, effective perpendicular thermal conductivity, resulting in a large volume

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of cold plasma and hence enhancing the radiative power in the boundary. Since this effective perpendicular thermal conductivity is proportional to the $7/2$ power of the temperature, the plasma may be stable thermally (Ref. 5).

If pellets are injected near the edge of the main plasma, then radial outward plasma flow can be maintained in the expanded boundary, provided that the same amount of the injected particle be pumped out. Near the very boundary, natural recycling provides a very strong plasma flow automatically. Unlike normal perpendicular plasma flow, this radial outward plasma flow can push the impurity outwards because it is plasma flow along the field line in this configuration and hence the friction force between ions and impurity pushes the impurities outward. Therefore, the impurities generated at the wall cannot enter the core, eliminating the impurity contamination problem. The plasma flow also leads to accumulation of thermalized α -particles and impurities for radiative cooling purposes in the boundary, thus making the ash removal substantially easier and enhancing boundary radiative power.

Since the pressure is constant in the destroyed flux surfaces, any radial fall-off in temperature will be compensated by a rise in the density and these two effects will further increase the radiative power. Therefore, effective radiative cooling may be realized, resulting in a very low plasma temperature at the limiter or wall and, consequently, minimization of the impurity generation and hence erosion of the limiter or wall.

One of the advantages of this approach is that deformation of the plasma chamber can be small, a feature which is very attractive from a reactor engineering perspective. Since the required helical field is very small, properly shaped ferromagnetic material, possibly located outside the blanket, can replace the helical winding coils, as is proposed in "Ferromak Stellarator" (Ref. 6); such insertions may be able to replace the helical coils. The disadvantages of such an approach are:

1. It works only when the q value of the boundary is the design value of the resonance structure that constitutes the magnetic island. Thus the discharge must be operated at the fixed total plasma current, hence sacrificing operational flexibility. For the same reason, it does not work in the startup phase of the

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discharge, during which period severe impurity contamination may take place. This may be an especially severe drawback in the case of reactor operation because achieving full plasma current will likely require several seconds.

2. Destroying the flux surfaces may increase the frequency of plasma disruptions.

The optimal means of implementing the expanded boundary configuration will ultimately depend upon the experience gained in the laboratory. The expanded boundary with deformed poloidal configuration is scheduled to be tested in the DIII facility and a reactor relevant test can be done in a possible DIII upgrade (large dee option). The expanded boundary with destroyed flux surfaces can also be tested with a modest cost because the required coil currents are very small.

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