RF Plugging of Mirror Plasma

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Discovery of superconducting materials that operate at high temperatures revive interest in the use of rf field for plasma confinement \cite{1}. This paper discusses feasibility of a scheme where resonant rf cavities are attached to the mirror ends of an open system for plasma confinement.

\textbf{KEY WORDS:} RF field; plasma confinement; mirror ends.

\section{1. INTRODUCTION}

In the late 1950s, several papers were published regarding the use of rf electro-magnetic field pressure to confine thermonuclear plasma by field buildup in a resonant cavity. These papers, as summarized by Glasstone \cite{2}, concluded that such an approach to fusion power was unpromising because Ohmic energy losses in cavity walls with normal conductors would be huge compared to all other energies involved, including possible thermonuclear yield, and because the electric field were impractically large (exceeding $10^6$ V/cm).

In the 1960s, high-Q superconducting cavities were developed \cite{3} that could reduce the Ohmic energy losses in the cavity walls. In a typical calculation of fusion energy balance, cavity Qs in excess of $10^6$ were required for the fusion power to exceed Ohmic losses. In fact, Qs exceeding $10^{10}$ have been achieved in empty cavities \cite{4,5}. Also during the 1960s, the electric fields of the order of $10^4$ V/cm were characterized as "about within the reach of current rf technology" \cite{6}. A general survey of to-date viewpoint on the plasma confinement by rf field has been elucidated by S.O. Dean \cite{1}. Here we discuss the use of superconducting rf-cavities to plug the plasma end losses from a mirror device. We restrict our consideration to only one but the key problem of the approach, namely that of damping of the rf oscillations at the plasma boundary.

The principal scheme of the device under consideration is shown in Fig. 1. To be more specific, we assume that the resonant cavities have cylindrical shape. Making this choice, we take into account that the axial symmetry of plasma body is crucial for reduction of transverse plasma transport.

\section{2. PRESSURE BALANCE}

If rf electromagnetic radiation impinging on the plasma boundary is largely reflected, it exerts the "pressure"

$$\left(\frac{E_\tau^2 + B_\tau^2}{8\pi} - \frac{E_n^2 + B_n^2}{8\pi}\right)$$

on the reflecting surface, where subscripts $n$ and $\tau$ denote components of the electromagnetic field normal and tangent to the surface respectively. As long as the plasma is considered to be an ideal conductor, $E_n = 0$ and $B_n = 0$ at its boundary. Then the equation (1) reduces to

$$\left(\frac{B_\tau^2 - E_\tau^2}{8\pi}\right)$$

The magnetic component of rf field really exerts a pressure while the electric field yields "tension of the field lines" and acts in the opposite direction. Thus we conclude that for better confinement the electric field must

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be zero at that part of the resonant cavity shell that faces the plasma.

A confined plasma exerts an outward pressure $nT$. This must be balanced by the radiation pressure $(B^2/8\pi)$. The overall equilibrium requires the ratio of these two pressures

$$\beta = \frac{8\pi nT}{\langle B^2 \rangle}$$

(3)

to be less than or at least equal to 1. Since the transverse equilibrium also requires a similar condition $\beta = 8\pi nT/H^2 < 1$ to be satisfied, the amplitude of rf field $E_{max} \sim B_{max}$ should be of the order of the ambient magnetic field $H$. We will refer the inequality $H < < B$ as the case of magnetic confinement, and the opposite inequality $H >> B$ as the case of rf-confined plasma.

The ideal case of complete normal reflection, discussed above, will be difficult to achieve in a resonant cavity that plugs longitudinal losses in an open confinement system. Indeed, the plasma boundary will not be smooth and flat because of radial dependence of the plasma pressure, it will not be sharp as the plasma may do some degree penetrate into the cavity. As a result, refraction and field rearrangement will occur. Furthermore, evanescent tails of the cavity’s electromagnetic field will penetrate into the plasma shell through the cavity’s opening and interact with the shell itself instead of the plasma. Thus, $\beta < 1$ is only a rough upper estimate, while the realistic value of $\beta$ will be lower, depending on the system design and plasma parameters. In particular, one possibility is the “close wave guide regime”, when the field frequency is so low that a corresponding wave cannot propagate along the waveguide formed by the plasma shell. We will briefly discuss this possibility in the concluding section.

3. CHOICE OF FREQUENCY

In the case of unmagnetized plasma, $H = 0$, an electromagnetic wave impinging on the plasma bound-