Plasma Confinement by Pressure of Rotating Magnetic Field in Toroidal Device

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Abstract:
Plasma confinement concept in which plasma is confined in a dynamic steady state by the pressure of rotating magnetic field in toroidal geometry is presented. The confining rotating magnetic field is created by AC currents driven by applying oscillating (with $f \geq 1$ MHz) voltages to toroidal and poloidal gaps in the shell of the torus with $\pi/2$ phase shift between these voltages. The toroidal component of magnetic field is created by oscillating poloidal current in the shell and the poloidal component of the field is created by toroidal image current on the plasma surface. Plasma equilibrium and stability are achieved due to the constraint of conservation of the amplitude of the oscillating magnetic flux through any section of the layer between the plasma and the conducting shell.

1 Introduction

Early ideas on plasma confinement by the pressure of rotating magnetic field were formulated in 1950s [1]-[3]. The magnetic vector rotates in the plane tangential to the plasma surface with frequency of rotation $\omega << \omega_{pe}$. Such an AC field penetrates unmagnetized plasma on a few skin depths and exerts almost time independent pressure on the plasma boundary, thus possibly insulating hot plasma from a wall of plasma containing chamber.

Initial analysis showed that the plasma boundary, supported by the rotating magnetic field, is unstable in the absence of a closely placed conducting wall. It was acknowledged [3], [4], [5] that a closely placed conducting shell can stabilize plasma boundary, but it seems that the physics of such stabilization was not clearly understood at that time and no practical device, realizing stable plasma confinement by the rotating field, was proposed. In experimental studies of plasma in rotating magnetic field [6]-[8] the conducting shell surrounding plasma played a “passive” role. Confining AC magnetic field was created (at least partially) by external windings and the gaps were made in the shell to allow magnetic flux penetrate inside the chamber. In these configurations the conducting shell was not a flux conserver and its effect on the plasma equilibrium and stability was significantly diminished.

The crucial innovation in the present confinement concept is the realization of the constraint of conservation of the amplitude of the AC magnetic flux in the layer between
the plasma and the conducting wall of the chamber. The confining field is created due to AC currents flowing in the closely placed conducting shell surrounding plasma volume. When the amplitudes of AC voltages applied to the gaps are fixed, the shell acts like a flux conserver and the currents in the shell adjust themselves to resist possible deformations of the plasma boundary providing for the plasma equilibrium and stability.

2 Toroidal Plasma Confinement

The proposed concept of plasma confinement by the pressure of the rotating magnetic field [9], [10] is illustrated in Fig. 1.

![Figure 1: Plasma confinement by rotating magnetic field tangential to the plasma surface.](image)

The confining rotating magnetic field is created by AC currents driven by applying oscillating (with $f \geq 1$ MHz) voltages to toroidal and poloidal gaps (insulated horizontal and vertical cuts) in the shell of the torus with $\pi/2$ phase shift between these voltages. The toroidal component of magnetic field is created by oscillating poloidal current in the shell and the poloidal component of the field is created by toroidal image current on the plasma surface. The frequency of rotation of the field, suitable for confinement, depends on the plasma temperature, such that the plasma boundary displacement during one field period (due to the toroidal effect) is insignificant.

The confining rotating field is localized in the vacuum layer, or a layer of a low loss dielectric, between the plasma and the toroidal shell, it penetrates plasma on a few skin depths [10]. Plasma discharge is created by the inductive electric field when the AC gap voltages are applied or by a preionization pulse. Plasma density in the discharge is defined by the initial gas pressure and plasma pressure is controlled by the applied voltages.

Toroidal plasma equilibrium and stability in this concept are achieved due to the realized constraint of conservation of the amplitude of the oscillating magnetic flux through
any section of the vacuum layer between the plasma and the conducting shell. The fast rotating magnetic field penetrates plasma and the conducting shell only on a few skin depths such that the magnetic flux is mostly localized in the layer between the plasma and the shell.

At the plasma and at the shell boundaries, the amplitude of the AC electric field (associated with the confining AC magnetic field) tangential to the plasma surface and to the surface of the conducting shell is zero (beyond the depth of the skin layer). According to the Faraday’s law of electromagnetic induction, assuming time dependence with the frequency \( \omega \), the flux of the amplitude of the AC magnetic field through any section of the layer between the plasma and the conducting shell is proportional to the AC voltage amplitude gained at crossings (if any) of such sections with the gaps in the toroidal shell. Such AC magnetic fluxes are conserved as long as the AC voltages applied to the gaps are fixed. With this constraint, a displacement of the plasma boundary toward the shell results in a local increase of time averaged magnetic pressure and restoration of the plasma equilibrium. In this concept a stabilizing feedback between the plasma boundary perturbations and the AC currents in the toroidal shell is realized.

3 Modeling of Plasma Equilibrium

Toroidal plasma equilibrium in this concept is modeled by using ideal MHD plasma model in 2-D by assuming axisymmetry, and thus neglecting the effect of the poloidal gap. Two approaches were examined: 1) calculating time evolution of the plasma column in the torus when the oscillating voltages \( V_p \) and \( V_t \) are applied [9] and 2) calculating the time averaged magnetic pressure on the plasma boundary due to these voltages. These two approaches demonstrated similar results for the equilibrium shape of the plasma boundary.

3.1 Time Evolution of the Plasma Column

In this model plasma is a perfectly conducting compressible fluid (ideal MHD model). AC magnetic field does not penetrate into the plasma column and it is localized in the vacuum layer between the plasma boundary and the shell. Boundary conditions at the surface of the toroidal shell are specified by the tangential components of the AC electric field (which models the applied AC voltages at the gaps) as,

\[
E_\theta = \frac{2\sqrt{\pi}}{\Delta \theta} e^{-\left(\frac{\theta}{\Delta \theta}\right)^2} \left[1 - e^{-\left(\frac{\theta}{\Delta \theta}\right)^2}\right] E_0 \cos \omega t,
\]

\[
E_\phi = \frac{R_0}{R_0 + \cos \theta} \left[1 - e^{-\left(\frac{\theta}{\Delta \theta}\right)^2}\right] E_0 \sin \omega t. \tag{1}
\]

The AC electric field at the shell’s boundary is gradually turned on on the time scale \( \Delta t \gg \omega^{-1} \). The initial plasma - vacuum boundary is a circle in the vertical section of the torus. The initial plasma pressure is such that it is approximately balances the time averaged magnetic pressure at the initial plasma boundary, estimated for the above boundary electric field at \( t \to \infty \). An additional artificial pressure, exponentially decaying
in time, is added in the vacuum to balance the plasma pressure until the boundary electric field amplitude reaches steady-state. The parameters used in the simulations: $R_0/b = 10$, $\omega b/c_s = 10$.

Figure 2: Profiles of plasma boundary. (a) plasma radius vs. time at $\theta = 0$ ($r_{p1}$) and $\theta = \pi$ ($r_{p2}$); (b),(c) time averaged plasma radius in poloidal cross-section

Figure 2(a) shows time dependence of the plasma radius at $\theta = 0$ (outboard side) and at $\theta = \pi$ (inboard side) versus time. Plasma column reaches dynamic steady-state in which the plasma boundary oscillates around its time averaged position with a small amplitude and frequency $2\omega$. These oscillations are due to the oscillations of the magnetic pressure within the field period, which are due to the toroidal effects. They vanish in the limit of the large aspect ratio. Figures 2(b) and 2(c) show time averaged plasma radius in the poloidal section. Plasma column is shifted in the outboard direction, similar to the Shafranov shift in tokamaks. This result also demonstrates vertical and horizontal stability of the plasma column in these simulations.

### 3.2 Plasma Pressure Balanced by the Time Averaged Magnetic Pressure

In this model the geometry of plasma boundary is calculated by assuming that the plasma pressure is balanced by the time averaged magnetic pressure of the rotating magnetic field. Plasma boundary is calculated as the surface along which the magnetic pressure is constant. The AC magnetic field in the vacuum layer in the torus is calculated from the Maxwell’s equations with the boundary conditions: 1) specified tangential components of the AC electric field amplitude on the inner surface of the shell, similar to the ones in Eqs. (1) for $t >> \Delta t$; 2) perfect conductor boundary conditions at the plasma-vacuum boundary.

Figure 3 shows geometries of the plasma boundary for different plasma minor radii and different aspect ratios of the device $R_0/b$. Outboard shift of the plasma column is larger for the smaller aspect ratio of the device.
Figure 3: Equilibrium plasma boundaries for different $a$ and $R_0/b$

The effect of the finite size of the gaps on the generated AC magnetic field is studied in the same model. Figure 4 shows the amplitude of magnetic field $B_\phi$ in the vertical section of the torus calculated with the finite width of the toroidal gap in the limit of large aspect ratio. The distortion of the AC magnetic field due to the gap affects the field in the vicinity of the gap on the distances comparable to the gap’s width. This result shows that plasma is almost unaffected by the finite width of the gaps when the width of the vacuum layer is larger than the width of the gaps.

Figure 4: Effect of the size of the gap on $B_\phi$

4 Plasma Stability

Plasma stability in this concept is analyzed in a simplified cylindrical geometry \[10\], demonstrating that the plasma boundary is MHD stable under nonrestrictive conditions. Plasma is modeled as a perfectly conducting compressible fluid with a vacuum layer between the plasma boundary and the conducting shell. Boundary conditions of the fixed tangential components of the electric field amplitude at the shell’s surface are applied. It is assumed that the frequency of the confining field is larger than the growth rate of
possible instabilities such that only the time averaged pressure of the AC magnetic field is considered. The flux amplitude conservation constraint is responsible for the plasma stability in the analyzed model. Similar results, but modified by the toroidal effects, are expected in the toroidal geometry.

Figure 5(a) shows stability diagram in the $\alpha$-plasma radius plane, where $\alpha$ is the ellipticity parameter of the AC magnetic field. $\alpha$ is proportional to the ratio of the applied voltages, as $V_t/2\pi R_0 = i\alpha V_p/2\pi b$. $\alpha = 1$ corresponds to the circular polarization of the AC magnetic field in the plane tangential to the plasma surface.

Plasma boundary is MHD stable when it is close enough ($a/b > 0.6$ for $\alpha = 1$) to the conducting shell. This condition is easy to realize in practical devices.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5}
\caption{(a) stability diagram $a/b$ vs. $\alpha$; (b),(c) profiles of AC magnetic field amplitude and density at the plasma edge}
\end{figure}

Figures 5(b),(c) show results of modeling of the AC field penetration into plasma. They show the amplitude of magnetic field profiles and plasma density profiles in the two fluid and fully kinetic models. Shell is located at $x = 0$ in these calculations. Rotating magnetic field penetrates plasma on a few $c/\omega_{pe}$. This justifies models with sharp plasma - vacuum boundary in the equilibrium and stability analysis.

5 Summary and Conclusion

The proposed concept of plasma confinement by the pressure of rotating magnetic field in the toroidal device passes initial theoretical examination of the plasma equilibrium and stability in the MHD model. The constraint on the AC flux amplitude conservation in the layer between the plasma and the shell, realized in the proposed toroidal device, suggests that plasma is expected to be in the MHD stable equilibrium in more complicated 3-D toroidal models and in experimental devices. Further theoretical and also experimental studies of this concept are needed to better evaluate its practical performance as the plasma confinement method.

The limitation on the plasma pressure is due to the AC power dissipation in the skin layer of the conducting shell such that a superconducting shell would be required for operation at high plasma pressures. Possible application of this concept to an efficient
fusion reactor depends on availability of superconductors (for the shell material) which can operate in magnetic field $\sim 1 \text{T}$ in $1 \text{MHz}$ frequency range. In a reactor, the solid dielectric layer between the plasma and the shell needs to be cooled by a liquid dielectric flowing in a cavity inside the solid dielectric.

References


