Studies on Self Organization of High βp Plasma near Equilibrium Limit and its Characteristics in the Spherical Tokamak QUEST

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論 文 名 : Studies on Self Organization of High β_p Plasma near Equilibrium Limit and its Characteristics in the Spherical Tokamak QUEST（球状トカマク QUEST における平衡限界近傍での高ポロイダルベータプラズマの自己組織化とその特性に関する研究）

区　　分 : 甲

論 文 内 容 の 要 旨

Plasma Magneto-Hydro Dynamics (MHD) equilibrium in a magnetic field is one of the fundamental research fields in laboratory, space, astrophysical and fusion plasmas. For a stable equilibrium, the plasma pressure needs to be balanced by the magnetic pressure which confines it. One of the long unresolved important aspect is how much maximum pressure that can be held in equilibrium for a given amount of magnetic energy. In tokamak configuration this is defined as plasma poloidal beta (β_p). Operating a tokamak at high β_p is usually attractive for utilizing a larger fraction of bootstrap current and reduce the external current drive requirement. This is particularly important along with a fully non-inductive current start-up and drive, for realization of Spherical Tokamak (ST) based fusion reactor, where limited or no center solenoid is in place. However, most of the earlier theoretical works have predicted an upper limit to this quantity called equilibrium β_p limit ($\varepsilon\beta_p \sim 1$), where plasma exhibits a very unique configuration bounded by a natural separatrix with a magnetic null suddenly appears at the inboard side of the device. Such configurations are rarely observed with extremely high bulk plasma heating or transiently appeared during initial plasma formation, which are not sustained enough to study its evolution and features. However, plasma self organization behavior which is prominently seen in many stabilizing phenomenon in plasma, may provide some relief to withstand such extreme situation.

High β_p plasma can be attained either (i) by an external source to heat the bulk Maxwellian component of the plasma or (ii) to create a confined anisotropic population of energetic particles or (iii) theoretical proposition about controlling its shape. In this study therefore, it is attempted to investigate all these aspects especially the later two methods. In previous work a confined anisotropic pressure of energetic electrons generated by LH waves ($p_{||} >> p_\perp$) has been shown to increase $\beta_{p.}$ In the present research, this anisotropic pressure is generated by injecting EC Waves ($p_\perp >> p_{||}$) and successfully confined by suitable magnetic configurations. On the other hand, to achieve high bulk pressure, the launched EC waves cannot be utilized as plasma becomes overdense too soon for the low B_t operation. Therefore, O-X-B mode converted EBWH/CD has been planned for QUEST. However, for effective mode conversion, O-mode waves need to be launched with optimal angle. This optimum angle can be determined by finding the viewing angle that maximizes the thermal emission (EBE) intensity from over-dense plasma. Therefore as a future scope of this study, a novel EBE diagnostics is developed in this work using a Phased Array Antenna to measure plasma EB emission. The third part of high β_p plasma study is effect of plasma shape. It has been proposed that with higher elongated (κ) plasma and suitable control of triangularity, high β_p plasma can be sustained. This aspect is investigated in the present research. Therefore the objective of this research is set to (1) Production and sustainment of high β_p plasma near the equilibrium limit with the help of non-inductive current drive, (2) Study of the equilibrium and its self organizing features as it approaches the limit. Accordingly, this thesis is organized as follows:

In Chapter 2, a brief description of tokamak QUEST and its various auxiliary heating systems used in this study are given in the first part. Second part of this section covers EBE diagnostics developed in QUEST along with in situ noise source calibration simulating a prospective mode conversion region and then reconstructing the intensity pattern as a proof of principle. Third part covers the 25 channel optic fiber based spectrometer system used in this study to measure and characterize intrinsic rotation in plasma. A simple model reconstruction for inverting line of sight measurement to find local velocity parameters is explained.

Chapter 3 deals in high β_p plasma experiments carried out in this research.

- In first part, plasma formation in fully non-inductive (NI) current drive is explained. In NI plasma, a very high β_p (~ 10) is produced at the beginning of the closed flux formation, with $\varepsilon\beta_p > 1$. As a result, equilibrium limit is reached with a spontaneous formation of Inboard Poloidal magnetic field Null (IPN), which is the characteristic signature of β_p limit. As the I_p is varied, a natural transition of equilibrium from IPN to Inboard Limiter (IL) and then IPN is self organized. β_p^* ($= \beta_p + l_i / 2$) decays as I_p^{-1}, independent of configuration and a natural transition discriminates IPN and IL, which is reported for the first time.
- To confirm the role of $<p>$ on the β_p, experiments are carried out in fixed I_p with the help of a Ohmic (OH) feedback circuit discussed in second part. It is demonstrated that with injection of ECRF (f = 8.2 GHz) to fixed I_p OH target plasma, very similar IL to IPN transition occurs with increase in β_p. The transition in configuration is studied as a function of applied B_z and the resulting β_p.
- Third part of this chapter describes experiment at second harmonic off-axis ECRF (f = 28 GHz) in OH plasma, where similar spontaneous formation of IPN is reported.
- In final section, summary of all the high β_p discharges are recapitulated, where the transition from IL to IPN at the critical $\beta_p^* > 3$ is very distinctly observed. This confirms that, IPN equilibrium formation is indeed due to the increase in plasma pressure and thereby resulting β_p, which is approached to its limit and results in formation of a natural magnetic null as predicted by theory.

In Chapter 4, some theoretical explanations of high β_p formation and a new feature of plasma self organization at negative triangularity is given with the help of a simple analytical model of Grad-Shafranov equation. The model result qualitatively explains the experimental findings. Chapter 5 concludes the thesis with some future scope of research are highlighted.

Some of the new results of plasma intrinsic rotation in high β_p IPN plasma are placed in Appendix. Sustained toroidal rotation up to 20 km/s is observed in IPN configuration, whereas no significant rotation is observed in IL plasma. It is observed that, substantial toroidal rotation exists even in open field line configuration, which is found to be originating near the ECR layer. The rotation in the open field lines later sustained and evolved to be present in steady state in a closed field line torus configuration.

In summary, producing a high β_p stable equilibria bounded by a natural magnetic null (IPN) with dominant component of non-thermal pressure sustained fully non-inductively in steadystate is the first of its kind experiment reported till date. In the present study it is demonstrated that plasma self organization feature is more dominant to adjusts its shape to remain in equilibrium and thus allowing a β_p limit. Intrinsic rotation in IPN plasma is a characteristic feature, which is found to be present even in the open magnetic field configuration. The detail physics of its origin and evolution remained to be investigated. Furthermore, the developed EBE diagnostic will be useful for carrying out efficient EBWH/CD experiments on QUEST and bulk pressure dominated high β_p plasma configurations may be investigated and compared with the present results.