32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-2.054 (2005)

Reproducible Appearance of Quasi Single Helicity State in a Reversed Field Pinch with an Appropriate Control of the Reversed Toroidal Field

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1. Introduction

A single helicity state in a reversed field pinch (RFP) is one of the configurations in which the sustainment of the RFP configuration by the dynamo action can be expected with a little (or possibly no) stochastic magnetic field. Experimentally, however, the single helicity state has not been realized so far. Instead the quasi-single helicity (QSH) state is observed [1]. In the QSH state one single helical mode of magnetic fluctuation becomes dominant, although other residual modes are not negligible and the stochasticity of the magnetic field line still remains, possibly with reduced level. Associating with the QSH state, the improved confinement was observed on TPE-1RM20[2], although the causality between the QSH state and the improvement was not clear since this improvement was always realized only with the high pinch parameter (Θ) and the beta stability limit of RFP would increase with Θ. The clear evidence of the QSH state in the plasma core was also shown on RFX, where the helical hot core was observed in the QSH state, and improved confinement was indicated in this region [3]. (Θ is the pinch parameter, $\Theta=B_{pa}/\langle B_t\rangle$ and F is the reversed parameter, $F=B_{ta}/\langle B_t\rangle$, where B_{pa} and B_{ta} are poloidal and toroidal magnetic field at the plasma surface, respectively.)

So far the appearance of the QSH, however, was spontaneous in experiments, the reproducibility of which is not sufficient. Therefore, the appearance of the QSH state was examined in a statistical way in several experiments, and the regions, in which the QSH states appeared with a relatively good probability, were found [4-6].

Recently a very interesting operating condition has been found in TPE-RX RFP experiment, where the QSH state is obtained with a very good probability, almost 100%, by the proper control of the waveform of B_{ta} after the setting up of RFP configuration. In this paper, the condition, by which a good reproducibility for the QSH state is obtained, will be described and the possible reason for it will be discussed.

2. The condition for reproducible QSH state and its sustainment

TPE-RX is one of the largest RFP machines in the world, where the major/minor radii are 1.72m/0.45m, designed plasma current I_p is 1MA and duration time is ~0.1s [7]. Typical parameters in the experiment described here are as follows; the peak I_p ~ 230kA, averaged electron density $n_e \sim (3 - 4) \times 10^{18} m^{-3}$, peak electron temperature T_e ~ 500-700eV and F/Θ ~ (-0.2-0.0)/(1.3-1.5). The fluctuation of toroidal magnetic field is measured by two arrays of 32 pick up coils which are located inboard and outboard sides on equatorial plane of the outer surface of the vacuum vessel.

The operating condition for obtaining the QSH state with a good reproducibility (almost 100%) is shown in Fig.1a, where the B_{ta} value is kept in a very shallow value (almost zero ~ -0.2mT) after the setting up and initial fast current rising phase. As shown in Fig.1c, after a certain period (~15-25ms) of the shallow B_{ta}, an m/n=1/6 mode rapidly grows and almost saturates before the termination of the discharge. The growth of this mode dominates over the others and the QSH state with m/n=1/6 is achieved.

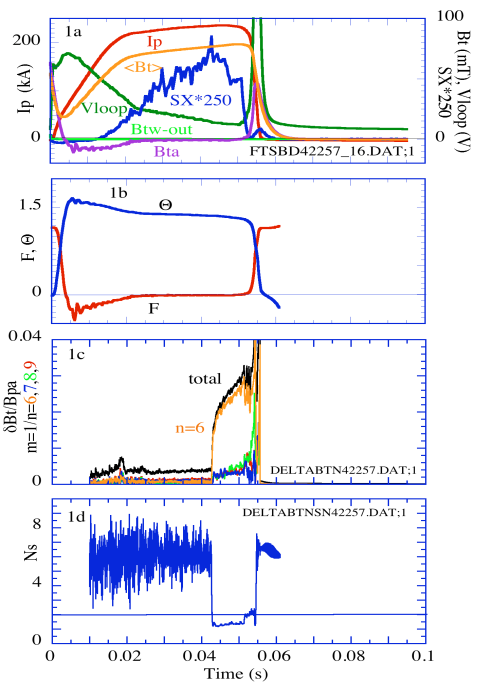

Fig.1 Discharge with the reproducible QSH state obtained by a very shallow reversal of B_{ta} (~0).

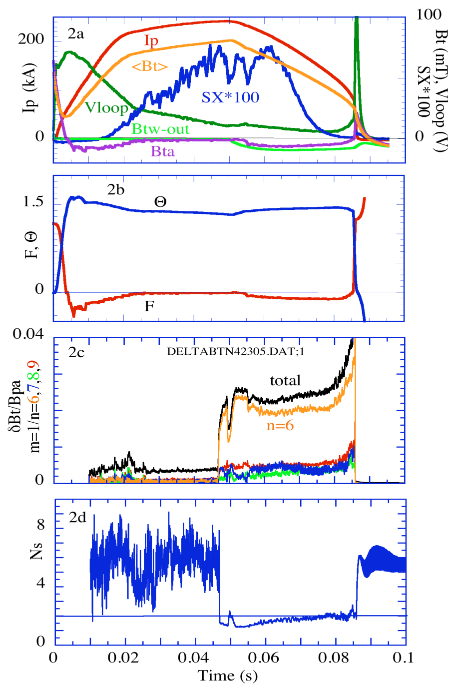

Fig.2 Discharge with prolonged QSH state by B_{ta} reversal (~10mT) with a delayed trigger (at 50ms).

Although this QSH state is terminated by the loss of B_{ta} reversal after ~10-20ms as shown in Fig.1, when a delayed B_{ta} reversal is applied with an appropriate trigger timing (at ~ 45-50ms) and magnitude (~ -(10-20) mT), it can be sustained much longer, nearly 45ms, with an ordinary Θ value (~1.4-1.6). However, the reproducibility of it is reduced to 85%, which is caused by the variations of the timing when the mode starts to grow in each shot. Fig.1d and 2d show the time dependence of QSH indicator (Ns) as defined in Ref. [8]. A very low value of Ns, ~1.2 is realized, which is close to the pure single helicity state where Ns should be one. It should be noted, however, that other modes having the helicities other than m/n=1/6 also grow simultaneously as shown Fig.1c and 2c, although their amplitudes remain small. Hence, the present QSH state is the result of overwhelming growth and saturation amplitude of one particular m/n=1/6 mode.

By using the standard α- Θ_0 model with $\beta_p = 0$ and 0.05, the magnetic field profile is estimated from experimental values of F and Θ. It is found that the m/n=1/6 mode is the innermost core resonant mode at the initial growing phase, and the time when this mode starts to grow agrees with that when a very small positive B_{ta} appears. This little positive B_{ta} seems to trigger the growth of the m/n=1/6 mode. The linear instability [9] is examined whether the m/n=1/6 mode has the largest growth late at this time by using the magnetic profile based on the α- Θ_0 model, and it is shown that the ideal mode with m/n=1/6 has the largest growth rate as expected. It is also found that the viscosity plays an important role to suppress the growth of modes with higher n.

According to the estimated q profile, the m/n=1/6 mode is innermost core resonant until ~70ms, then, the innermost resonant mode changes to m/n=1/7 since the central value of safety factor (q_0) is decreasing as the F is becoming deep. The precise time of this change is determined by the time variation of magnetic field profile, which depends also on the plasma pressure. Central q_0 will increase as β_p increases. Therefore, the change of the innermost resonant mode will be delayed when the β_p is large. Since the pressure profile is not known, the extreme case with β_p=0.1 is examined and it is shown that this change occurs at ~ 80ms even with β_p=0.1. Possibly the actual change occurs between 70 and 80ms. An interesting observation is that the QSH state with m/n=1/6 survives even after this change although the m/n=1/6 mode has no resonant surface.

The non-linear 3-D calculation [9] is used to consider the mechanism of the growth and saturation of m/n=1/6 mode. In the calculation, boundary conditions simulating the actual situations in TPE-RX are considered, such as the highly resistive first wall of vacuum vessel, closely fitted thin copper shell and thick ideal shell rather far from the plasma. The results of 3-D calculations can also qualitatively simulate the experimental observations, where the m=1/n=6 mode becomes dominant and saturates after the initial relaxation phase.

3. Summary

In the RFP experiment on TPE-RX, the QSH state can be obtained with an almost 100% reproducibility by using the very shallow reversal of B_{ta} (keeping B_{ta} almost zero). This QSH state with ordinary Θ value (~1.4-1.6) can be sustained for up to ~45ms with slightly reduced reproducibility (~85%) by applying the additional B_{ta} reversal with delayed trigger (at ~ 45-50ms with ~ - (10-20) mT peak value). The QSH indicator Ns, as low as ~1.2, is realized during this period. The onset mechanism of this QSH state is examined by the numerical calculation. The initially growing m/n=1/6 mode is linearly unstable to the ideal MHD instability. The 3-D simulation can also show the selective growth of this mode during the relaxation.

Acknowledgement

This study was financially supported by the Budget for Nuclear Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan, based on the screening and counseling of the Atomic Energy Commission.

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