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EQUILIBRIUM IN HIGH BETA LOW MAGNETIC FIELD DISCHARGES OF URAGAN-2M

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It has been shown that the plasma beta ($\beta = nT/(\mu_0 \cdot B^2)$) is relatively high in low magnetic field ($B_T \approx 0.01$ T) radio frequency discharges of the URAGAN-2M (U-2M) stellarator. This high beta is achieved in the low temperature ($T_e = (10…50)$ eV) and density ($n_e = (0.5…1) \cdot 10^{12}$ cm^{-3}) due to the very low magnetic field. In this work, we calculate the plasma equilibrium in these discharges using the VMEC code, with experimental density, temperature and plasma current values. The radio-frequency current drive can compensate the bootstrap current if the current directions are opposite, according to our calculations. This current drive can partially compensate U-2M equilibrium deterioration due to plasma beta effects. This effect may explain the experimentally observed dependence of the achieved plasma beta on the magnetic field direction in U-2M.

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INTRODUCTION

The violation of plasma confinement in magnetic traps can be caused by various phenomena such as bootstrap current, β-effects, error-field, etc. Stellarators rely on currents in external coils to provide the magnetic fields with the rotational transform needed for plasma confinement and stability. The radial profile of the rotational transform, ι(r), is a key design parameter of these configurations and can be chosen to exclude formation of the low-order rational surfaces inside the plasma. Nonetheless, the current in the plasma of stellarators can be substantial, and finite plasma beta effects cannot be completely compensated. These factors can modify the designed equilibrium. Strong plasma current can lead to the deterioration of stellarator discharges.

The appearance of various 1…20 kHz MHD oscillations was reported in U-2M low magnetic field (B = 0.01 T) discharges [1, 2]. The plasma beta parameter is relatively high in these discharges despite the low temperature and density [1, 2]. Substantial modification of the designed magnetic configuration of U-2M due to plasma beta results in confinement degradation and, as a consequence, the excitation of these MHD oscillations.

In this work, we present further studies of these low magnetic field discharges in different magnetic field directions. The VMEC code [3] was recently adopted for U-2M using the ideal *l* = 2, *m* = 4 stellarator approach [4]. We use VMEC for equilibrium modeling of these discharges in our work.

CONDITIONS AND DIAGNOSTICS

In our experiments, the frame-type antenna (FTA) and three half turn (THT) antenna simultaneously were used in low magnetic field B≈0,01T ($\omega >> \omega_{ci}$) hydrogen discharges. The conditions for radio frequency U-2M plasma heating and major diagnostics are described in Ref. [1]. The Tripple Langmuir probe (TP) is used for measurement of complete profiles up to plasma center (Fig. 1) in cold, low density RF discharges under consideration. A comparison of the TP measurements and conventional single pin scanned LP measurements shows good agreement [1].

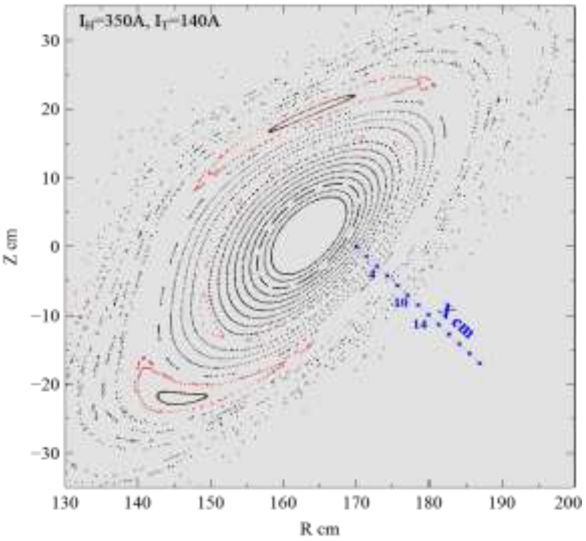

Fig. 1. Triple probe positions across vacuum magnetic flux surfaces

Additionally, we are using a recently installed Rogowski coil for plasma current measurement in our work. This coil is located close to the TP toroidal location. This location is almost opposite to the FTA and THT toroidal locations [1]. Strong noise suppression technique was used in hardware design [5].

EXPERIMENTAL RESULTS

Time traces of major plasma parameters in normal and reverse magnetic field directions are shown in Fig. 2.

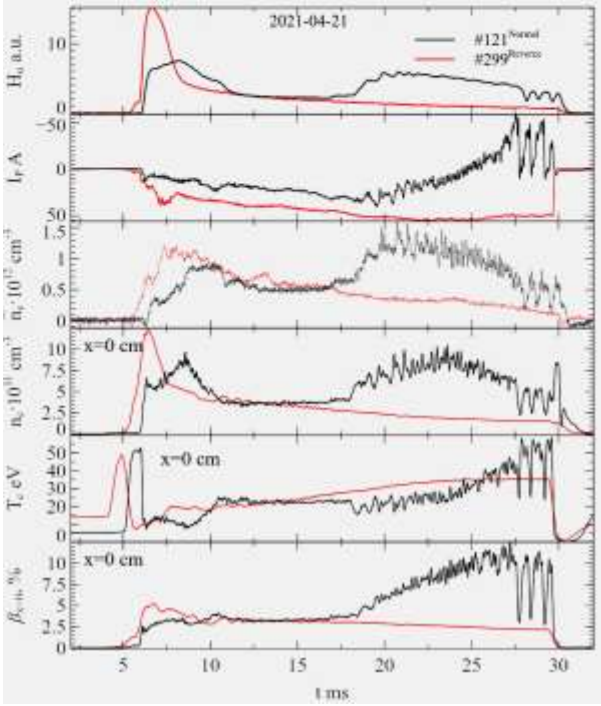

Fig. 2. B_T≈0.01T RF discharges in normal (#121 in black) and reverse (#299 in red) magnetic field directions

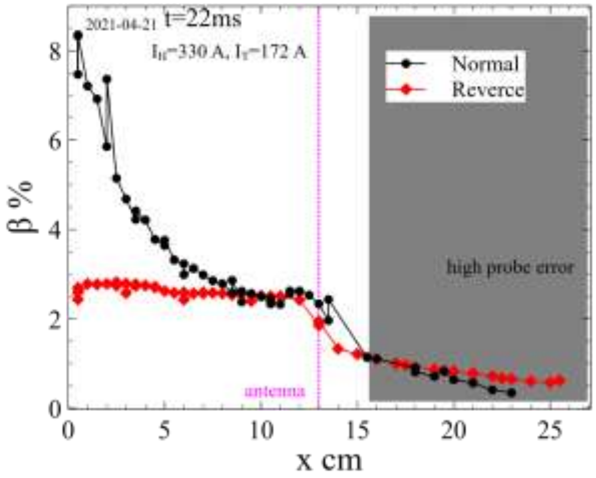

Fig. 3. Radial profiles of RF discharges in normal and reverse magnetic field directions at t=22ms

The same RF power, U-2M coil currents (I_T =172 A, I_H =330 A), and pre-filled hydrogen pressure are used in these discharges. The line-averaged electron density n_e was measured by the interferometer and compared with the local n_e measured by the triple probe (TP) in the deepest manipulator position, as described in Ref. [1] and sown in Fig. 1.

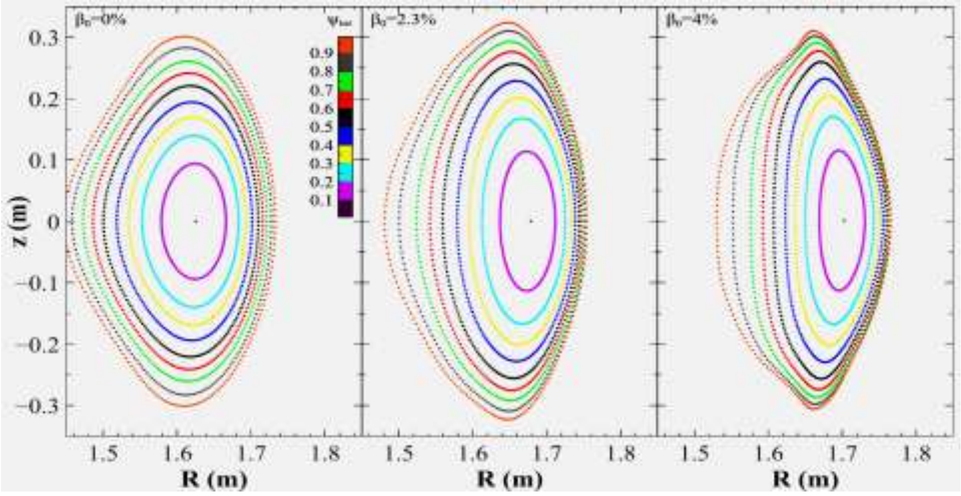

Fig. 4. U-2M magnetic flux surfaces and rotational transform profiles calculated for 3 plasma beta cases

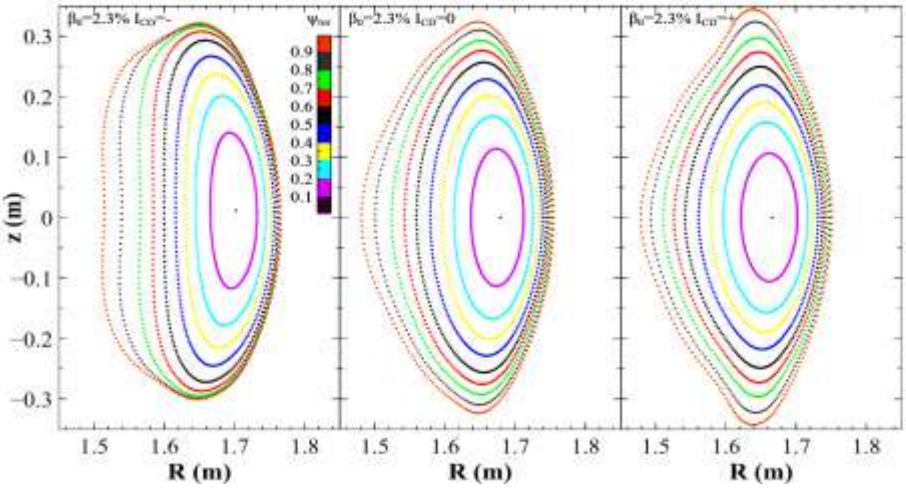

Fig. 5. U-2M magnetic flux surfaces for β_0=2.3% and RF current drive. The RF current drive in co and counter bootstrap current directions are marked by $+I_p$ and $-I_p$

The local plasma beta was calculated using only the electron component in the deepest TP position. Radial profiles of the local plasma beta calculate electron component are shown in Fig. 3.

A set of similar discharges are used for TP radial position scan depicted in Fig. 3. A systematic overcome of plasmabeta was observed in similar U-2M discharges with normal B_T directions, under various vacuum magnetic configurations and pre-filled pressure conditions.

It is expected that the RF current drive (I_{RFCD}) is independent of the magnetic field direction, while the bootstrap current (I_{BS}) direction changes if the currents in the magnetic field coils of U-2M are reversed. Thus, if I_{RFCD} is opposite to I_{BS}, partial compensation of these currents is possible.

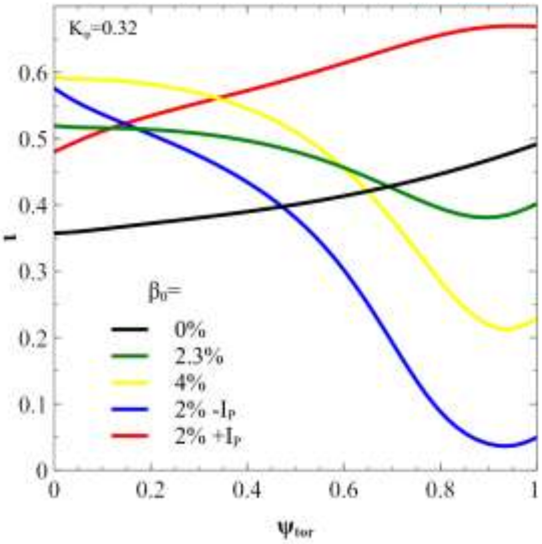

Fig. 6. U-2M ι profiles for different β_0 cases. The RF current drive in co and counter bootstrap current directions are marked by $+I_p$ and $-I_p$

VMEC MODELING

The free-boundary setup of the VMEC code is used in our modeling. Despite the complex experimental profiles (see Fig. 3), parabolic plasma pressure profiles are used in our calculations. The equilibrium modification due to the plasma beta effect alone, without external current drive, is shown in Fig. 4. Since U-2M is not an optimized stellarator, even moderate β_0 = 2…4% values substantially modify the magnetic surfaces. The ι profile becomes non-flat, and low-order rational surfaces appear in this profile (Fig. 6). These low-order rational surfaces can lead to confinement degradation and, in particular, to the MHDactivity previously observed in low magnetic field discharges in U-2M [1]. The appearance of these MHD modes depends on the magnetic topology and has also been observed in the hot plasma of different stellarators, such as W7-AS [6], TJ-II [7], and W7-X [8–10].

The application of external current drive introduces additional modifications to the equilibrium. These modifications for the parabolic current profile, experimental total current value, and different current directions are shown in Fig. 5.

As depicted in Fig. 6, the distortion of the ι profile due to plasma beta is enhanced when the plasma current direction coincides with the bootstrap current direction (blue curve in Fig. 6). The shape of the flux surfaces also becomes different from the vacuum magnetic configuration (see Figs. 4 and 5). In the opposite case (red curve in Fig. 6), the ι profile is as flat as the vacuum profile (see black curve in Fig. 6), and the shape of the magnetic surfaces is also less perturbed. Thus, the current drive can partially compensate distortion of the magnetic surfaces due to plasma beta effects if the bootstrap and current drive currents directions are opposite. In this case rather high β values can be achieved even in the non-optimized stellarators such as U-2M.

The parabolic modeling profile of the plasma beta is different from the experimental profile depicted in Fig. 3. This experimental profile is measured along the line of the TP manipulator's movement (see Fig. 1). This line crosses the center of the vacuum magnetic flux surfaces, and the TP almost reaches the center (see Fig. 1). Although the modification of the equilibrium causes not only a modification of the rotational transform but also changes the shape of the flux surfaces and introduces a Shafranov shift in the plasma center position, in this case, the line of the TP measurement is shifted from the plasma center position. This shift is demonstrated in Fig. 7.

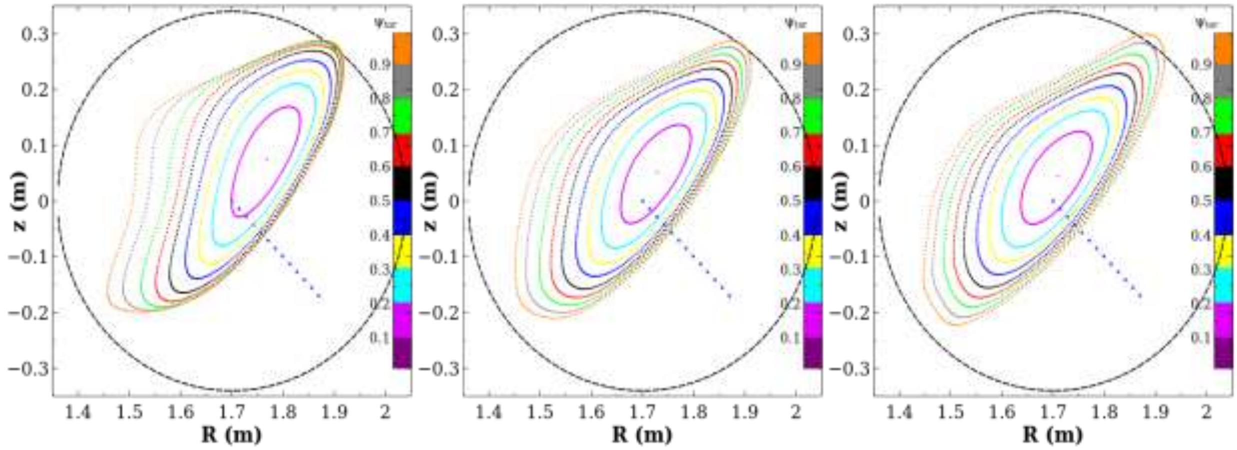

Fig. 7. U-2M magnetic flux surfaces in the TP cross-section for β_0=2.3% and RF current drive. The RF current drive in co- and counter-bootstrap current directions is marked by $+I_p$ and $-I_p$, respectively. The TP movement line is shown as a blue dashed line

The location of the TP measurement point is shifted non-radially due to the distortion of the magnetic surfaces. Therefore, an accurate remapping of the 3D location of the TP measurement point to the normalized radius is required for the interpretation of the Fig. 3 data. The VMEC equilibrium recalculation is needed after such remapping, as this data serves as input for the VMEC code. A set of iterations is required for accurate mapping of the TP movement line and for the convergence of the calculations. For this reason, we are using parabolic profiles to qualitatively demonstrate our observations. Even though these calculations are qualitative, the results provide an understanding of the compensation of the flux surfaces due to the bootstrap current by the external current drive.

SUMMARY

We present the first observation of plasma confinement dependence on the magnetic field direction in $B_T \approx 0.01$ T, $n_e \approx 10^{12}$cm^{-3}, $T_e = 30$ eV discharges of Uragan-2M.

The VMEC code has been used for simulation of RF discharge in Uragan-2M for the first time.

If the RF current drive direction is opposite to the bootstrap current produced by the plasma β, then the distortion of the magnetic surfaces can be compensated, and rather high β values can be achieved even in the non-optimized stellarator Uragan-2M.

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РІВНОВАГА РОЗРЯДІВ ВИСОКОГО БЕТА НИЗЬКОГО МАГНІТНОГО ПОЛЯ В УРАГАНІ-2М

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Показано, що бета плазми ($\beta = nT/(\mu_0 \cdot B^2)$) є відносно високим у радіочастотних розрядах слабкого магнітного поля ($B_T \approx 0{,}01$ Т) стеларатора УРАГАН-2М (У-2М). Таке високе бета досягається незважаючи на низьку температуру ($T_e = 10…50$ еВ) і густину ($n_e = (0{,}5…1) \cdot 10^{12}$ см$^{-3}$) через дуже низьке магнітне поле . У цій роботі ми обчислюємо рівновагу плазми в цих розрядах за допомогою коду VMEC на базі експериментальних даних густини, температури та струму плазми. Згідно з нашими розрахунками, струм, який створюється радіочастотним нагріванням, може компенсувати бутстреп струм, якщо ці струми спрямовані у протилежні сторони. Цей струм може частково компенсувати погіршення рівноваги У-2М через бета-ефекти плазми. Цією компенсацією може пояснити залежність досягнутого бета плазми від напрямку магнітного поля в У-2М, що і спостерігалось в експериментах.