Overview of Experimental Studies on IR-T1 Tokamak

Pejman Khorshid 1), M. Ghoranneviss 2), M. Razavi 1), S. Saboohi 2), M. Mollai 1), A. Hojabri 2), D. Dorranian 2), M.K. Salem 2), R. Tarkeshian 2), R. Arvin 2), S. Mohammadi 2), A. Talebitaher 2), A. Nikmohammadi 2), M.R. Yousefi 2), A. Shokouhi 2), A.H. Sari 2) and IR-T1 team 2)

1) Department of Physics, Mashhad Campus, Islamic Azad University, Mashhad, Iran
2) Plasma Physics Research Centre, Science and Research Campus, Islamic Azad University, Tehran, Iran

e-mail contact of main author: pkhorshid@gmail.com

Abstract. An overview of experimental studies on IR-T1 tokamak is presented. Several issues of plasma displacement measurement are investigated. An analytic solution of the Biot–Savart law, which is used to calculate magnetic fields created by toroidal plasma current, is presented. Results of calculations are compared with the experimental data obtained in no-plasma shots with a toroidal current-carrying coil positioned inside the vessel to simulate the plasma movements. The results show a good linear behavior of plasma position measurements. An array of Mirnov coils employed for measurement of plasma position, too. The results show that Mirnov array can not be used for this measurement without concerning high field side errors. An external resonant helical magnetic field (RHF) applied to plasma. The aim of these experiments was to understand the effect of RHF on light impurities radiation and horizontal displacement measurements. Measurements results of visible line emissions of O^{II}, C^{III} impurities and H_α radiation with and without RHF (L=2) show that the addition of a relatively small amount of resonant magnetic helical field (L=2 & L=3) could be effective for improving the quality of the discharge by reducing of light impurities radiation. The effect of RHF in plasma displacement measurement shown an increase in flux value about %5 for L=2, L=3 separately and about %10 for L=2&3 when apply together. In other experiments, Studies of plasma interaction with titanium coated ferritic steel have been performed. Depth of impurity penetration and retention, and the surface roughness were measured using surface analysis methods. The results show that titanium acts as an effective getter for oxygen but its fast erosion poses a problem. A change in roughness with respect to position of samples has been observed.

1. Introduction

IR-T1 tokamak is an ohmically heated air core tokamak with major radius R=0.45 m and minor radius a=0.125 m defined by two poloidal stainless-steel limiters. The vacuum chamber has circular cross-section with two toroidal breaks and minor radius b=0.15 m. Toroidal magnetic field B_t~0.6-0.8 T, plasma current I_p~25-30 kA, averaged electron density 1-2×10^{19} m^{-3} in hydrogen, plasma discharge duration t_d~30ms and electron density $T_e(0)$~200 eV. The tokamak also has external resonant helical field (RHF) coils. The main goals of IR-T1 tokamak are studies of Magnetohydrodynamic (MHD) activities, tokamak edge physics and developing the plasma physics education. In this contribution the work developed on IR-T1 tokamak will be presented as plasma displacement measurements, applying a resonant helical magnetic field on plasma and plasma wall interaction.

2. Plasma Displacement Measurements

In several configurations of magnetically confined plasmas, the position of the plasma column is a major determinant of plasma behavior for controlling the plasma equilibrium. Several methods are employed for displacement measurements, such as optical and magnetic methods. For the magnetic method, almost it is used sine-coil. The Ampere's theorem and the Biot–Savart law are well known tools used to calculate magnetic fields created by current distributions [1-4]. The former is often used in high-symmetry problems of magnetisms. At first section of this work, an analytic solution of the Biot–Savart law, which is used to calculate magnetic fields created by toroidal current-carrying coil positioned inside the vessel to simulate the plasma movements, is presented.

In the second section a sine-coil, which is a Rogowski coil with a variable wiring density is designed and fabricated for measurement of no-plasma shot experiments with circle coil of radius R=0.45 m. The last section contains measuring the poloidal magnetic field components with discrete pick up coils placing diametrically on the outer surface of torus.

2.1. Biot-Savart Analytical Magnetic Field Measurment

Now we try to use the Biot-Savart law to calculate the field in the toroidal coordinate of the circular wire coil of radius r = 0.45 cm. According to Maxwell equation the magnetic field, B, is given by $\vec{\nabla}\times\vec{B}=\mu_0\vec{J}$, since the $\vec{\nabla}.\vec{B}=0$ and using expression of $\vec{\nabla}.(\vec{\nabla}\times\vec{F})=0$, we can write $\vec{B}=\vec{\nabla}\times\vec{A}$, where J is current density and A is vector potential so that the above expression yields,

$$\vec{A}(\vec{r})=\frac{\mu_0}{4\pi}\int\frac{J(\vec{r}^{\,'})}{\left|\vec{r}-\vec{r}^{\,'}\right|}dv' \tag{1}$$

and by defining $\vec{J}(\vec{r}')dv'=\vec{I}dl$, B(r) leads to,

$$\vec{B}(\vec{r})=\frac{\mu_0 I}{4\pi}\oint_c\frac{d\vec{l}\times(\vec{r}_2-\vec{r}_1)}{\left|\vec{r}_2-\vec{r}_1\right|^3} \tag{2}$$

This equation has been solved using a numerical method, and the topology of the whole magnetic fields calculated. The result has been investigated for measurement of current carrying coil position with respect to sine-coil position. In this calculation, we fixed the sine-coil position and moved the current coil in horizontal direction. The results of flux calculation by Biot-Savart law has been compared with experimental data as shown in FIG.1. The error is less than 2.5% and it has been compared with other methods of measurements of the plasma position [5].

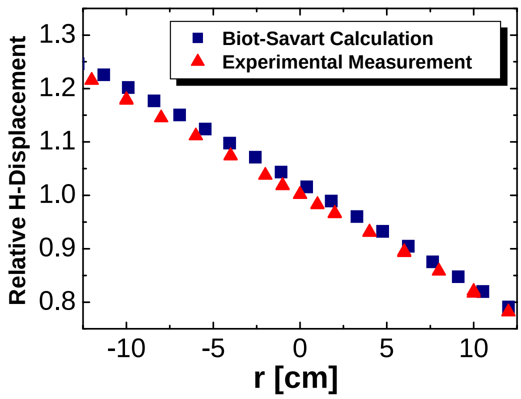

FIG. 1. Comparison of calculations with actual plasma position. The rectangle and the triangle symbols show the Biot-Savart law calculation and the measurements with the sine-coil, respectively.

2.2. Plasma Displacement Measurements via Discrete Method

This is one of the simple possible techniques, which measures the local values of poloidal magnetic field at some points around the plasma by placing magnetic probes diametrically opposite for magnetic field measurement. Combination of the signals produced by these probes is proportional to the displacement of the plasma column. In this method, twelve Mirnov coils has been used. The results shown that high field side effect needs correction for horizontal displacement measurement.

3. Resonant Helical Field Experiments

The RHF in IR-T1 tokamak is an external magnetic field which can improve the plasma confinement. This field is produced by two winding with optimized geometry conductors wound externally around the tokamak torus with a given helicity. The minor radius of these helical windings are 22cm (L=2, n=1) and 23cm (L=3, n=1). In the experiments presented here, the current through the helical windings was between 100-400A, which is very low compared with the plasma current itself (25-30kA).

3.1. Effect of RHF on Light Impurities Radiation

The aim of these experiments was to understand the effect of RHF on light impurities radiation and suppressing major disruptions. The length and the magnitude of the pulse feeding the helical windings could be programmed. Measurements results of visible line emissions of O^{II} (4416A°), C^{III} (4644A°) impurities and H_α (6563A°) radiation with and without RHF (*l*=2) show that the addition of a relatively small amount of resonant magnetic helical field could be effective for improving the quality of the discharge by reducing of light impurities radiation and possible suppressing major disruptions. FIG. 2 shows the measurement results of visible line emissions of O^{II} (a, b), C^{III} (c, d) impurities and H_α radiation (e, f) with and without RHF (L=2) [6].

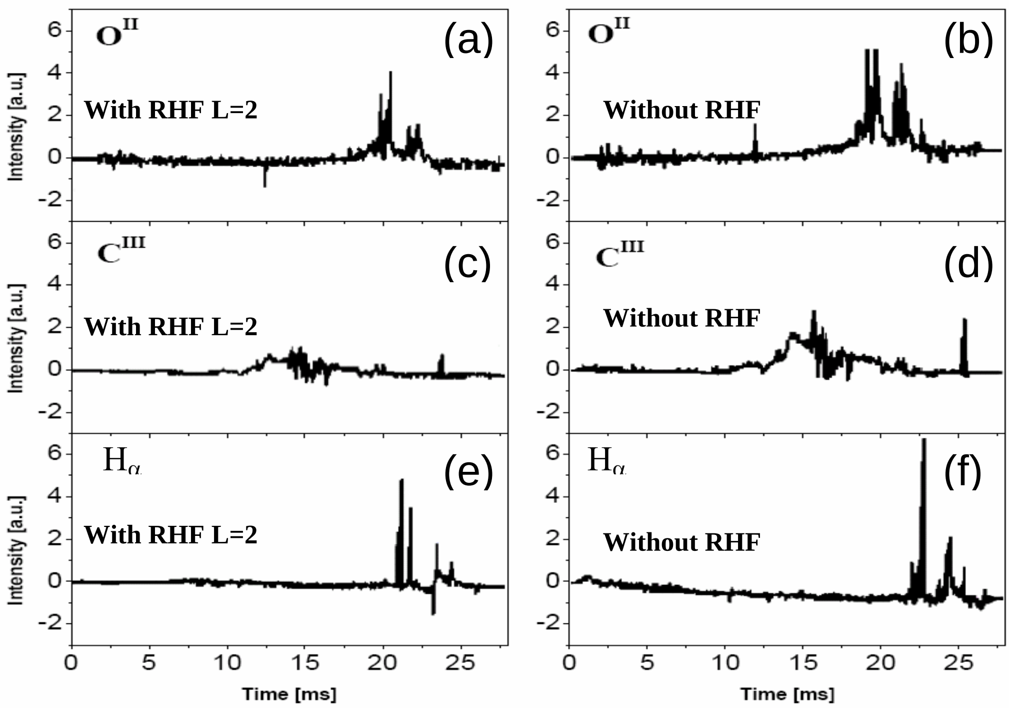

FIG. 2. The measurement results of visible line emissions of O^{II} (a, b), C^{III} (c, d) impurities and H_α radiation (e, f) with and without RHF (L=2).

3.2. Effect of RHF on Plasma Displacement

The plasma displacement measured during Resonant Helical Field application in L=2, L=3 and L=2&3. The results shown an increase in flux value about %5 for L=2, L=3 and about %10 for L=2&3. FIG.3 shows typical Schematic of L=2/1 and L=3/1 RHF winding coil around the chamber and effect of RHF with different mode on plasma horizontal displacement. It shows the Magnetic field calculation from RHF via Bio-Sawart law in best position 0°, 45°, 145° for installing Sine-Coil and a sample magnetic field calculated in the 120° as a high nonlinear effective position.

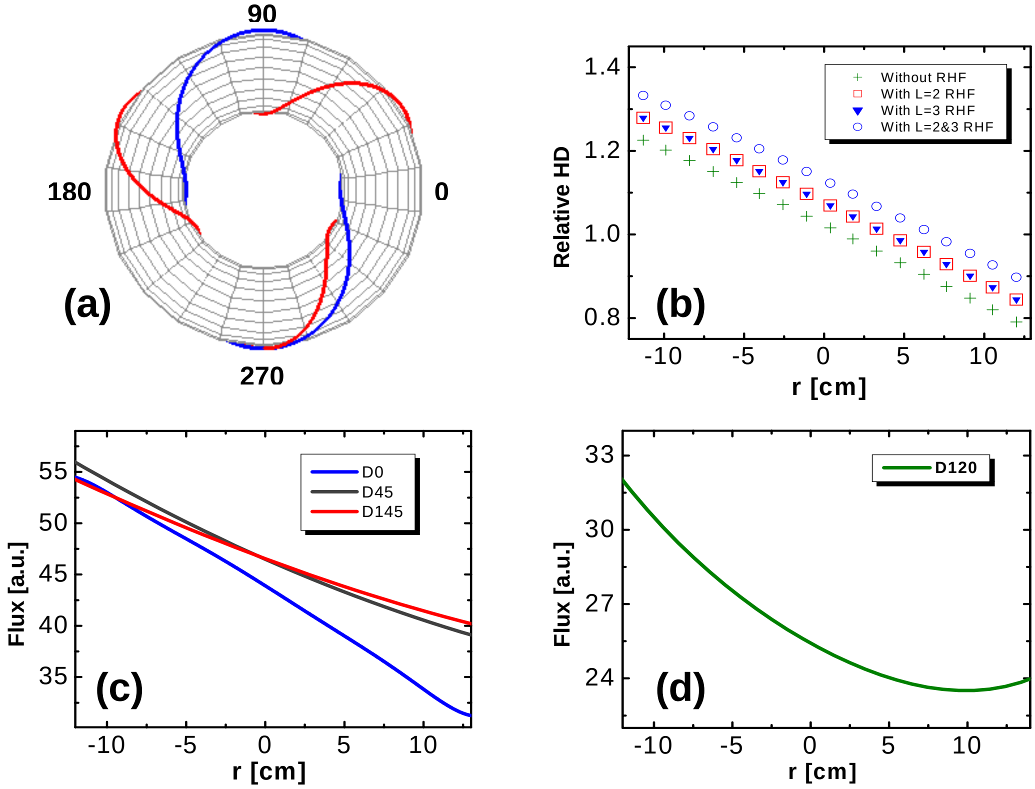

FIG. 3. a) A typical Schematic of L=2/1 and L=3/1 RHF winding coil around the chamber, b) Effect of RHF with different mode on plasma horizontal displacement, c) Magnetic field calculation from RHF via Bio-Sawart law in best position 0°, 45°, 145° for installing Sine-Coil, d) A sample magnetic field calculated in the 120° as a high nonlinear effective position.

4. Study of Plasma Wall Interaction

Studies of plasma interaction with titanium coated ferritic steel have been performed on IR-T1 tokamak. The main aim of this experiment is to understanding effects of glow discharge and plasma on the edge surfaces positioned in the wall and limiter area of IR-T1 Tokamak for future studies. We use RF sputtering method with power 400 W and deposit titanium layer on ferretic steel substrate, as a protect coating. Some of steel substrates baked in 460ºC temperature and for 3 hours before analyzing them. Also, we installed some samples on flange at different depth from plasma core (r=0) in IR-T1 Tokamak in r_1=12.5 cm, r_2=13.2, r_3=13.5, r_4=13.8, r_5=14.2 cm, respectively. The samples positioned in parallel array. The experiments carried out with 15 minute glow discharge cleaning and 55 plasma shots.

Surface roughness of samples obtained by AFM (Atomic Force Microscopy). We can see an obvious decrease at surface roughness of samples at different depth from plasma core due to energetic sputtered particle impact effect on the nearest sample from plasma core. Energetic particles have decreased when they impact to the far sample, and damaging the surfaces decreased. FIG. 4 shows changes in roughness in samples before and after 55 plasma discharges and FIG. 5 shows profile of comparing roughness of samples before and after discharges [7].

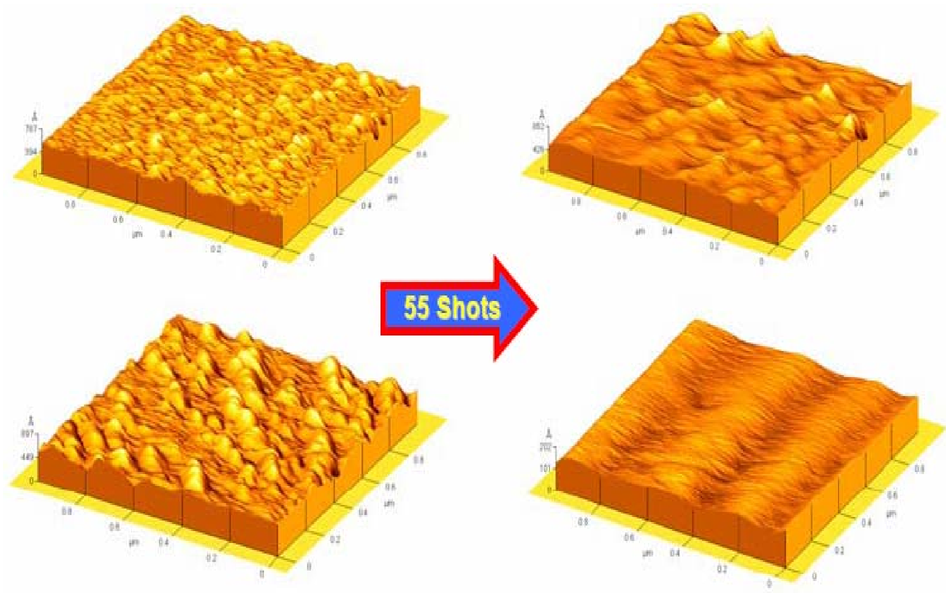

FIG. 4. Changes in roughness at two different positions of the sample with respect to plasma core. Below one is closer to plasma core. Left figures are before discharges and right figures are after discharge.

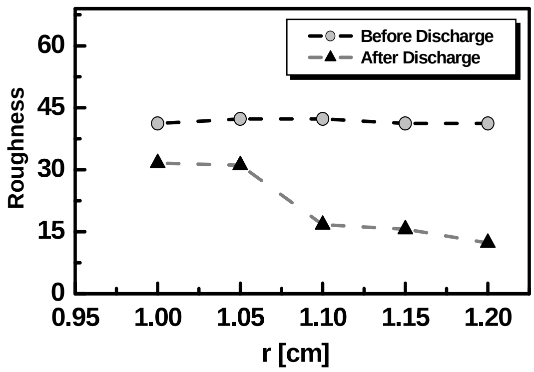

FIG.5. Profile of comparing roughness of samples before discharge and after discharges, where, r (normalized) is the position of samples with respect to plasma core.

Rutherford Backscattering Spectrometry (RBS) spectra method has been used to measure the content of Oxygen and Titanium, before and after discharges. Simulation was done by SIMNRA software as a routine tool to simulate RBS spectra [8-11]. RBS spectra of Ti layer on Steel obtained by 2000 keV incident on energy at α=0 degree, β=15 degree and θ=165 degree.

We set up samples with different condition but replaced them in the same distance from plasma core in IR-T1 Tokamak. RBS spectra show lower oxygen content in survivor sample after plasma-surface interaction in titaniumized sample (FIG. 6). It may be due to oxygen gettering of titanium properties. Coated steel capture amount of oxygen by titanium layer, then titanium layer with content of impurity (oxygen) eroded from surface because of surface defects. So, we can see lower content of oxygen in this sample. This result isn't good conclusion because of plasma purity, but it generally emphasis to lower oxygen penetration or permeability in steel and titanium impurity absorption. The result is shown in Table I.

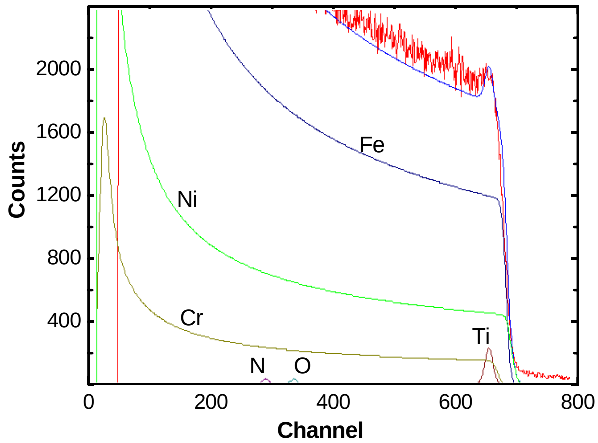

FIG. 6. The analyses of RBS measurements with SIMNRA Code.

TABLE I: OXYGEN GETTERING EFFECT OF T_i LAYER.

Samples	**Thickness (°A)**	**Ti (%)**	**O_2 (%)**
With out Baking (r3186-1-Ti)	200	50	50
After Baking (r3188-2-Ti)	100	40	60
After Baking (r3191-4Ti)	100	35	65

5. Conclusion

- Comparing the results of the model experiment we conclude that the sine-coil can be exploited for measurement of plasma displacement in the IR-T1 tokamak. The error is less than 2.5% and it has been compared with other methods of measurements of the plasma position. In addition, this method will be used in the feedback position control system and tests of feedback controller parameters.

- During Resonant Helical Field application the experimental results suggest that the addition of a relatively small amount of resonant magnetic helical field (L=2 & L=3) to the basic torus configuration could be effective for improving the quality of the discharge by reducing of light impurities radiation and suppressing major disruption. Also, the structure of magnetic field lines in tokamak with RHF has been investigated by means of analytically calculation of the Biot–Savart law. The behaviour of plasma displacement is different when the L is different. It is found that in both cases, RHF influences on displacement measured by sine-coils. The results shown an increase in flux value about %5 for L=2, L=3 separately and about %10 for L=2&3 when apply together. Therefore RHF can influence in Plasma displacements and then on the plasma feedback control, so it needs some consideration in the results.

- Plasma interaction with Titanium coated ferretic steel has been performed on IR-T1 Tokamak. AFM analyses before and after discharge in r=12.5-14.2 cm carried out. The results shown that, we should use methods that decrease titanium erosion.

Titanium-substrate adhesion and coating technique should be modified, thickness of layer may be help us in this way, and we must use ferretic steel with different composition such as type of ferretic steel with no content of nickel or less chromium content. Depth of impurity penetration and retention, and the surface roughness were measured by using Rutherford Backscattering Spectrometry (RBS) spectra method has been used to measure the content of nitrogen, oxygen and titanium, before and after discharges. The result has been shown a change in roughness with respect to position of samples. Also, the results shown that the concentration of oxygen decreases after titanisation.

References

[1] CHEN L., ZHAO Q., ZHU Y., FANG Z., FAN H., "Measurement of plasma position on HT-7 tokamak" Journal of Fusion Engineering and Design, **34-35**, 721 (1996).

[2] CHOUDHURY M.H., "Electromagnetism" John Wiley and Sons, New York (1989).

[3] CHARITAT T. and GRANER F., "About the magnetic field of a finite wire", Eur. J. Phys. **24**, 267 (2003).

[4] CAVALLERIY G., SPAVIERIZ G. and SPINELLI G., "The Ampere and Biot–Savart force laws" Eur. J. Phys. **17,** 205 (1996).

[5] KHORSHID P., et al., "Designing a Sine-Coil for Measurement of Plasma Displacements in IR-T1 Tokamak" AIP Conf. Proc. Volume 996, pp. 224 (2008).

[6] HOJABRI A. et al "Effect of rotating magnetic helical field on the impurity radiation and the magnetic island in IR-T1 Tokamak" 32nd EPS, Tarragona, Spain, ECA 29C, P4.064 (2005).

[7] GHORANNEVISS M. et al., "Study of Plasma Interaction with Titanium Coated Ferritic Steel in IR-T1 Tokamak", AIP Conference Proceedings, Volume 996, pp. 172 (2008).

[8] ZINKLE S.J., et al., "Effect of initial oxygen content on the void swelling behavior of fast neutron irradiated copper", J. Nucl. Mater. 329-333, 919 (2004).

[9] APICELLA M.L., et.al, "Effects of wall titanium coating on FTU plasma operations", ECA, VOL.**24B**, 1573 (2000).

[10] TSUZUKI K., et al., "High performance tokamak experiments with a ferritic steel wall on JFT-2M"**,** Nucl. Fusion **43,** 1288 (2003).

[11] MAYER M., SIMNRA, "A Simulation Program for the Analysis of NRA, RBS", American Institute of Physics Conference Proceedings, **475**, 581 (1999).