Experimental study of the electromagnetic fluctuations and plasma confinement in the quasi-axisymmetric stellarator CFQS-T

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1. Introduction

The electromagnetic fluctuations have an important impact on plasma transport and confinement in magnetic confined fusion devices, such as tokamaks [1], and stellarators [2], etc. As for a newly developed magnetic confined fusion device, studying the characteristics of the electromagnetic fluctuations and plasma confinement in the experiments is an important research topic, which can help to understand the characteristics of the new device and find solutions to improve plasma confinement in future experiments.

The Chinese First Quasi-axisymmetric Stellarator Test device (CFQS-T) has been successfully commissioned in August 2024 [3, 4], which is the first experimental phase of the Chinese First Quasi-axisymmetric Stellarator (CFQS) [5-7], operating at low magnetic field strength (< 0.1 T) and low heating power (< 30 kW) conditions. From December of 2024 to May of 2025, various working gases, such as argon, helium, hydrogen, and deuterium, have been used in the CFQS-T experiments. In the second experimental phase of CFQS, it will operate at the designed magnetic field strength (B_{T0}= 1 T) with much higher heating power (~ 500 kW) as scheduled by the end of 2026.

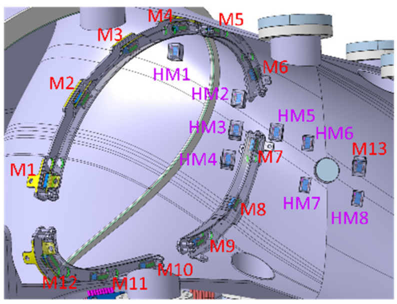

Figure 1. Layout of low frequency and high frequency magnetic probe arrays on CFQS-T.

This work will introduce the initial experimental study of the electromagnetic fluctuations and plasma confinement with newly developed magnetic probe arrays [8, 9] and other diagnostics on CFQS-T.

2. Experimental study of the plasma fluctuations and confinement in CFQS-T

2.1 Frequently observed electromagnetic fluctuations in argon plasmas on CFQS-T

Low-frequency electromagnetic harmonic modes with a frequency of 1-5 kHz are frequently observed in argon plasma discharges on CFQS-T. A typical discharge is shown in figure 2. In this discharge, the electric current through a modular coil I_{MC} is set to 237 A (figure 2(a)), which corresponds to B_{T0}=0.05 T as shown in figure 2(b). The argon is used as the working gas, which is heated by the electron cyclotron heating system with a magnetron frequency of 2.45 GHz and a maximum injecting power of 10.5 kW, as shown in figure 2(c). The time evolutions of the line-averaged electron density signal and visible light signal without a filter are shown in figure 2(d) and (e), respectively. Figure 2(f) shows the spectrogram of the visible light signal, in which electromagnetic harmonic modes with frequencies from 1-5 kHz are observed. The time evolution of a poloidal magnetic signal and its spectrogram are shown in figures 2(g) and (h), respectively. The similar harmonic modes are also observed in the spectrogram of the magnetic signal. The harmonic modes evolve into quasi-coherent modes with a higher frequency at ~4 s. The propagation characteristics of the electromagnetic modes are studied with high frequency magnetic probe array (HFMPA) as shown in figure 2(i) and (j). Both the harmonic and quasi-coherent modes are poloidally propagating in the electron diamagnetic drift direction.

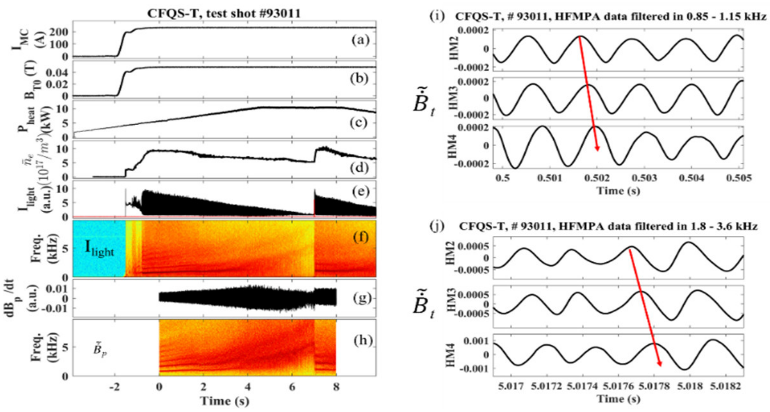

Figure 2. (a)-(h) Time evolution of physical parameters in the argon plasma discharge on CFQS-T, (i) and (j) poloidal propagations of the electromagnetic fluctuations in frequency band of 0.85-1.15 kHz and 1.8-3.6 kHz in this discharge respectively.

2.2 Frequently observed electromagnetic fluctuations in helium plasmas on CFQS-T

Higher frequency electromagnetic quasi-coherent modes are usually observed in helium plasma discharges compared with argon plasma discharges on CFQS-T. But the poloidal propagation of the modes is similar to the low-frequency modes observed in Ar discharges. A typical helium discharge is shown in figure 3. The electromagnetic quasi-coherent modes with frequency of 2-12 kHz are observed in this discharge, and it propagates poloidally in the electron diamagnetic drift direction as shown in figure 3(i).

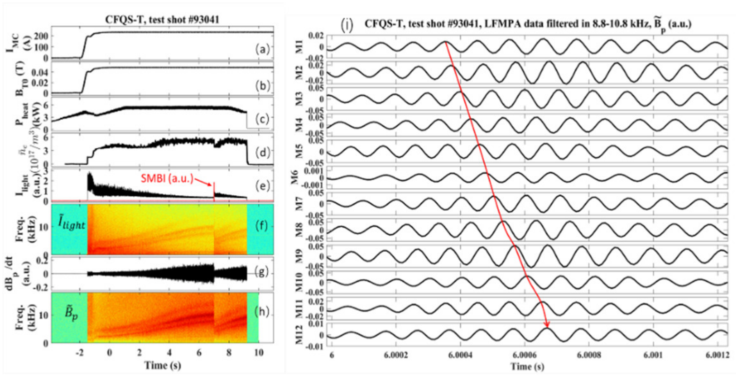

Figure 3. (a)-(h) Time evolution of physical parameters in the helium plasma discharge on CFQS-T, (i) poloidal propagation of the electromagnetic fluctuations in frequency band of 8.8-10.8 kHz in this discharge.

2.3 Frequently observed electromagnetic fluctuations in hydrogen plasmas on CFQS-T

The electromagnetic quasi-coherent modes are also frequently observed in the hydrogen plasma discharges, whose frequencies are usually higher than argon plasma discharges on CFQS-T. In some low plasma density but relatively high heating power discharges, high-frequency magnetic modes can also be observed. A typical discharge is shown in figure 4, as the 12 kW heating power was put in, the electromagnetic quasi-coherent modes with frequencies of 3-25 kHz appeared (see figure 4(h)), it poloidally propagated in the electron diamagnetic drift direction and toroidally propagated in the counter-B_T direction. When the plasma density and radiation power suddenly dropped at ~5 s, high-frequency (70-160 kHz) bursting magnetic modes were observed. And its propagation directions are the same to the low-frequency quasi-coherent modes in this discharge.

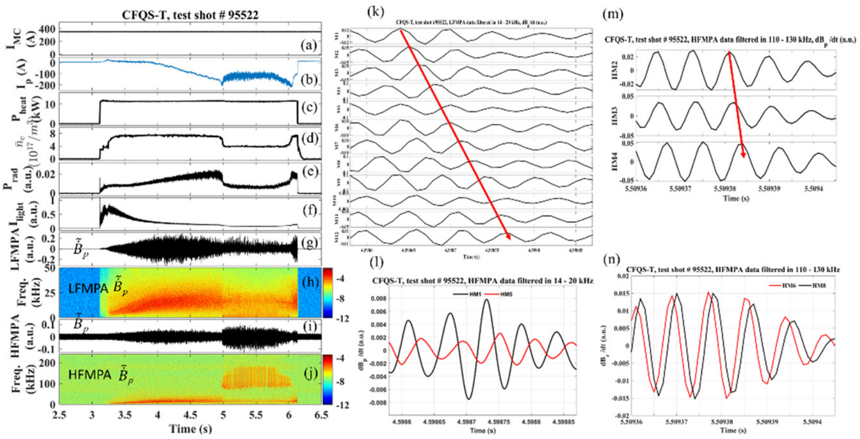

Figure 4. (a)-(j) Time evolution of physical parameters in the hydrogen plasma discharge on CFQS-T, (k) and (l) poloidal and toroidal propagations of the electromagnetic fluctuations in frequency band of 14-20 kHz in this discharge, (m) and (n) poloidal and toroidal propagations of the electromagnetic fluctuations in frequency band of 110-130 kHz in this discharge.

2.4 Initial analysis of the plasma confinement in CFQS-T

The plasma energy confinement time in CFQS-T is also preliminarily studied. Due to the low plasma stored energy and unstable differential-integrator of the diamagnetic loop diagnostic on CFQS-T. The plasma stored energy measurements are not available for every discharge. A typical discharge with good plasma stored energy measurements is shown in figure 5. Two heating systems are used in this discharge with a total injecting power of 21 kW, and the plasma stored energy reaches 160 J. With different estimated heating power absorption coefficients, the plasma energy confinement time τ_E is in the range of 10-40 ms between 3.1 - 8.0 s in this discharge.

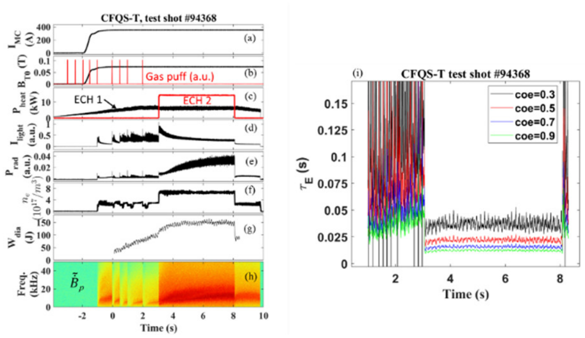

Figure 5. (a)-(h) Time evolution of physical parameters in the hydrogen plasma discharge on CFQS-T, (i) plasma energy confinement time τ_E calculated with different estimated heating power absorption coefficients.

2.5 Runaway discharges in CFQS-T

During the CFQS-T experiments, some runaway discharges are identified with the radiation detectors around the machine. Since the radiation detectors will make alarm noises when the runaway discharge occurs. Two typical hydrogen plasma runaway discharges are shown in figure 6. Both of them are triggered by the radiation collapses as shown in the fifth panels of figure 6(a) and (b). But only in one discharge #95097, the high frequency (100-250 kHz) bursting magnetic modes are observed in the later time, which may be due to the lower electron density and higher runaway current in this discharge, as shown in the figure 6.

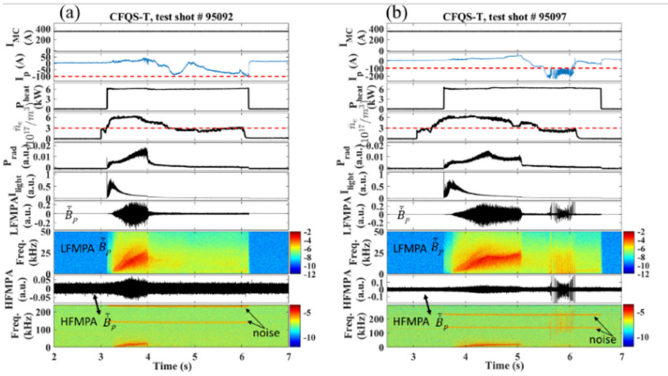

Figure 6. (a) and (b) Time evolution of physical parameters in the two hydrogen plasma runaway discharges on CFQS-T.

3. Summary and future work

The frequently observed electromagnetic fluctuations on CFQS-T stellarator with different working gases, such as argon, helium, and hydrogen, are studied. The plasma energy confinement in CFQS-T is also preliminarily studied. Runaway discharges are also presented in this work. In the near future, more systematic modeling and experimental studies will be carried out on electromagnetic fluctuations observed on CFQS-T.

Acknowledgements

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References

[1] M. Yoshida, et al., 2025 Nucl. Fusion 65 033001.

[2] D. A. Gates, et al., 2018 Journal of Fusion Energy 37:51–94.

[3] J. Cheng, Progress of the Chinese First Quasi-axisymmetric Stellarator (CFQS) construction and preliminary experimental studies, 24th International Stellarator Heliotron Workshop, 9-13 September 2024, Hiroshima, Japan

[4] H. Lan, et al., Development and preliminary application of the magnetic diagnostics on CFQS-T, 24th International Stellarator Heliotron Workshop, 9-13 September 2024, Hiroshima, Japan

[5] Y. Xu, 2020 Stellarator News 170.

[6] H. F. Liu et al., 2021 Nucl. Fusion 61 016014.

[7] A. Shimizu et al., 2022 Nucl. Fusion 62 016010.

[8] H. Lan, et al., 2025 submitted to Fusion Eng. Des.

[9] H. Lan, et al., 2025 to be submitted to Acta Phys. Sin.