Study on the Behavior of High Energy Electrons in REPUTE-1 ULQ Plasmas

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Abstract. In REPUTE-1 Ultra-Low-q (ULQ) plasmas, behaviors of high energy electrons have been studied through a low-Z pellet injection experiment, in addition to the measurements of soft-X ray PHA and Electron Energy Analyzer(EEA). The high energy tail has been measured in the soft-X ray spectrum, and EEA signal has shown a strong anisotropy of the electron distribution function (i.e., the electron flux to the electron drift side is dominant). To study temporal and spatial information on these high energy electrons, a low-Z pellet injection experiment has been conducted. A small piece of plastic pellet is injected from the top of the REPUTE-1 device, and the trajectory of the pellet inside the plasma is measured by CCD camera. We have observed a large deflection of the pellet trajectory to the toroidal direction opposite to the plasma current (i.e., the electron drift side). This suggests that a pellet is ablated selectively only from one side due to the high energy electrons with a large heat flux. We have calculated the heat flux carried by high energy electrons. Since the repulsion force to the pellet can be calculated with the 2nd derivative of the pellet trajectory, we have estimated the heat flux of high energy electrons to be a few tens MW/m^2 around the plasma center. Experimental data by EEA measurement and low-Z pellet ablation show the large population of the high energy electrons at the core region in comparison with the edge region, suggesting a MHD dynamo mechanism for the production of the high energy electrons..

1. Introduction

We have been studying Ultra-low-q (ULQ) plasmas not only for exploring compact fusion reactors but also for understanding plasma physics in the intermediate regime between tokamak and RFP (e.g., in ULQ plasmas the stability with negative shear configuration has been intensively studied, and dynamo effect plays an essential role, as well.[1]). In ULQ plasmas some interesting features such as anomalous plasma resistance, strong ion heating and high energy electrons have been observed experimentally, similar with those in RFP plasmas. Especially, production mechanism and radial transport of these high energy electrons give a fruitful information on ULQ/RFP plasma dynamics such as MHD/kinetic dynamo mechanism and stochastic transport due to electromagnetic fluctuations. MHD dynamo predicts that the high energy electrons might be produced at the core region[2], while kinetic dynamo, where electrons are accelerated by the applied electric field during the travel along stochastic magnetic field, produces a large population of high energy electrons at the edge region of the plasma column[3]. To this end various experiments have been conducted in RFP plasmas[4]. Here we have studied the behavior of high energy electrons in REPUTE-1 ULQ plasmas with various measurements; i.e., soft X-ray PHA, Electron Energy Analyzer (EEA) and low-Z pellet injection.

2. Measurements of High Energy Electrons by Soft X-ray PHA and Electron Energy Analyzer

Typical parameters of REPUTE-1 ULQ plasmas are as follows; the major/minor radii of plasma are 0.82m/0.22m, respectively, and the toroidal magnetic field is 3.5 kG. The plasma current is typically 100 – 200 kA, and a stepwise change of the plasma current takes place. At first, we have examined a high energy component of electrons with soft X-ray PHA[5]. High energy tail extending up to a few keV has been observed in low bulk electron temperature plasmas(T_{bulk} = 30 ~ 100 eV).

To study the electron distribution function, the EEA detector has been inserted at the outer region of the plasma column. By rotating the head of the EEA detector at the fixed radial position, the electron flux has been measured for various angles to the magnetic field line. Figure 1 shows the EEA signal at r/a=0.73 as a function of the rotation angle. The direction of the local magnetic field has been measured with the magnetic probe set up with the EEA detector, as well. We have observed a strong anisotropy of the electron flux in the EEA signal; i.e., a clear peak of the EEA signal can be seen at the angle of the local magnetic field in the electron drift side. While, the very weak peak at the opposite side (ion drift side) appears, as shown in Fig. 1. By the way, we should notice that the ULQ plasmas behave a stepwise change of the plasma current as a function of time. Then, we have observed a drastic change (or disappearance) of the EEA signal according to the change of the plasma current.

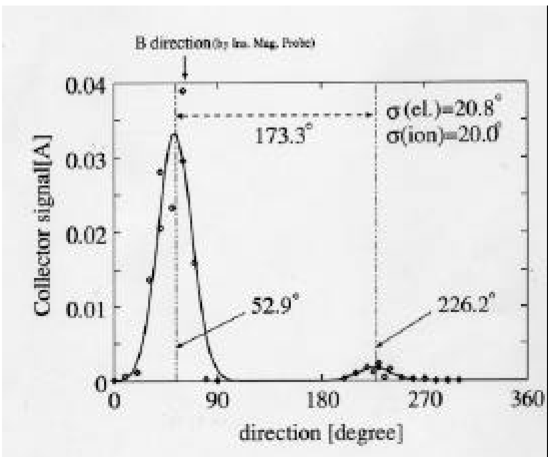

Fig. 1 Signal of the Electron EnergyAnalyzer(EEA) as a function of the rotating angle at r/a=0.73. The direction of the magnetic field measured is also depicted.

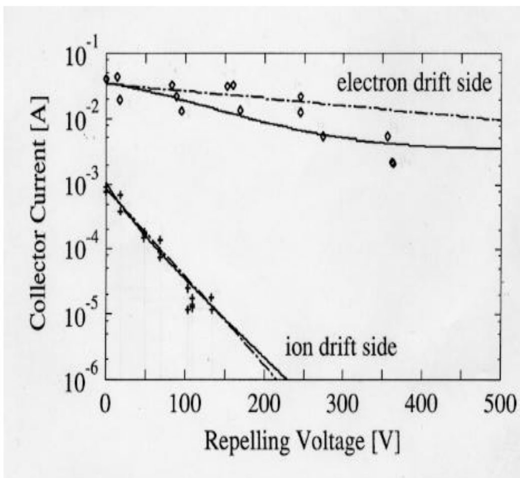

Fig. 2 The electron flux as a function of a repelling voltage for electron and ion sides.

A repelling voltage is applied in the EEA detector so as to measure the electron distribution function. Figure 2 shows the electron flux for electron/ion drift sides as a function of the repelling voltage, and a clear difference between electron and ion drift sides is observed. The electron distribution function of the electron drift side is extending up to a few hundreds volts, while that of the ion drift side drastically decreases.

A population of the high energy electrons has been measured by scanning the EEA detector inside the plasma at relatively low plasma current (I_P=50kA). At the edge region of the plasma column (r/a > 0.8) a drastic decrease of the high energy electron has been observed. It has been estimated that the current carried by these high energy electrons could be dominant for the total plasma current.

3. Low-Z Pellet Injection Experiments

Since a pellet injected into plasmas is strongly ablated by high energy electrons, ablation behavior of the pellet crossing the plasma column could give a radial population of high energy electrons. Ice pellet injection experiments in RFP plasmas have been carried out in ZT-40M[6] and RFX[7], and a strong deflection of the pellet trajectory has been observed. In RFX pellet experiments, the deflection of the pellet trajectory due to high energy electrons seems to be consistent with the MHD dynamo theory[8].

Comparing the ablation process between ice and low-Z pellets, the neutral gas shielding effect is quite small in low-Z pellet ablation, because of the large difference of the evaporation energy (typically, the evaporation energy of plastic pellet is roughly two orders of magnitude higher than that of hydrogen ice pellet), resulting in lowering a neutral gas density in low-Z pellet case. We have calculated the pellet ablation rate for both cases (neutral gas shielding model and no shield model) with the ablation code, and found the difference of the ablation rate between two model is quite small in the case of low-Z plastic pellet.

The direct evaporation by the anisotropic heat flux due to high energy electrons becomes dominant in REPUTE-1 ULQ plasmas. This directly affects on the pellet trajectory; e.g., the anisotropy of the heat flux yields the large deflection of the pellet. In addition, the amount of the ablated particle number of low-Z pellet is estimated to be at most 1 % of the bulk density. This is preferable from the viewpoint that the perturbation to the bulk plasma dynamics is quite small. The low-Z pellet is, therefore, a useful diagnostic tool for studying the high energy electrons in REPUTE-1 ULQ plasmas

A small piece of plastic pellet with a size of 0.3 – 0.5 mm diameter is injected from the top in the REPUTE-1 device, and the trajectory of the pellet inside the plasma is measured by CCD camera system equipped at the horizontal port. To inject the pellet from the top of the device, the guide pipe of the pellet is bended at the right angle. It is confirmed that the plastic pellet does not split into several fragments when the pellet is bended, and the incident pellet speed is decelerated about 20% by this bending guide pipe[9].

Figure 3 shows the typical photograph measured by CCD camera with CI optical filter(538 nm). The waveform of the plasma current is given in Fig. 4, where the pellet is injected at the time of t = 2.0 msec. It takes about 3 milliseconds to cross the plasma column, because the pellet speed is typically 130 – 160 m/sec. In Fig. 4 we can see a clear deflection of the pellet trajectory to the toroidal direction opposite to the plasma current (i.e., the electron drift side). This suggests that a pellet is ablated selectively only from one side due to the high energy electrons with a large heat flux. Figure 5 shows the relation between the local intensity of CI line and the local deflection rate (i.e., the 2nd derivative of the pellet trajectory), suggesting a strong correlation between each other. Around the plasma center a strong deflection of the pellet trajectory takes place, accompanied by the remarkable increase of the intensity.

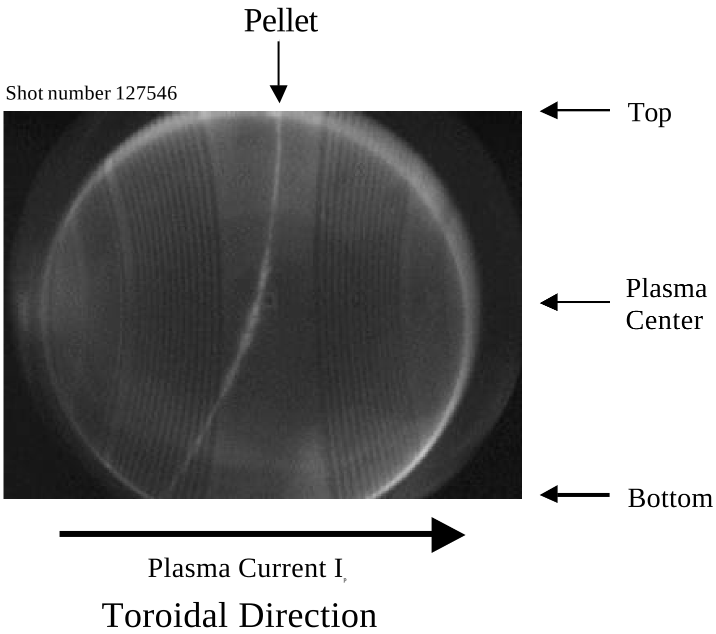

Fig. 3 Photograph of the pellet trajectory measured with CCD camera in REPUTE-1 ULQ plasmas. The pellet is injected from the top of the torus. The large deflection of the pellet trajectory opposite to the plasma current (i.e., electron drift direction) can be seen.

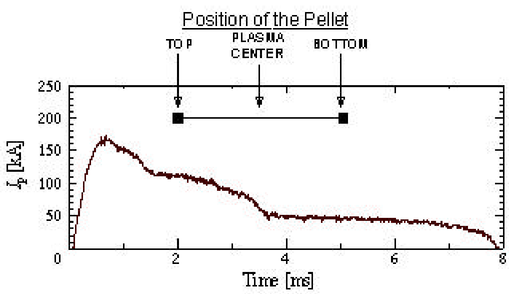

Fig. 4 The waveform of the plasma current. The pellet is injected at t=2msec, and it takes 3msec crossing the plasma column.

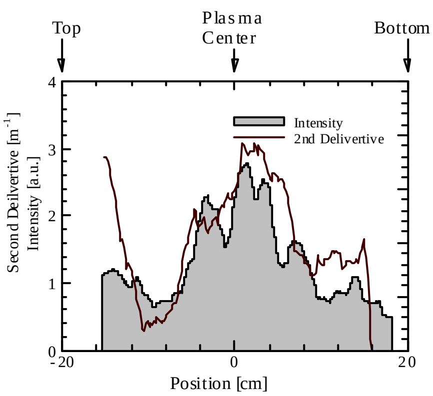

Fig. 5 The intensity of the CCD camera and the 2nd derivative of the pellet trajectory, related with the repulsion force acting on the pellet.

Here let us discuss on the heat flux carried by high energy electrons, by evaluating the deflection of the pellet trajectory shown in Fig. 3. We assume that the electron drift side of the pellet is selectively ablated by the heat flux of high energy electrons and the neutral gas spouts only from the electron drift side with the thermal velocity of the evaporation temperature. Neutral gas, therefore, yields the repulsion force acting on the pellet itself to the toroidal direction. Since the repulsion force to the pellet is calculated with the 2nd derivative of the pellet trajectory, we can estimate the heat flux of high energy electrons, and the maximum heat flux around the plasma center is calculated to be 20 – 40 MW/m^2. Since the ohmic input power is around 10 MW, a few tens percentage of the input power might be carried by the high energy electrons.

We can see in Fig. 5 that the pellet trajectory is strongly bended around the plasma center, suggesting a large population of high energy electrons. It is also confirmed in the EEA data that the population of the high energy electrons around the edge region is small. Therefore, our results on EEA measurements and low-Z pellet experiments could support MHD dynamo mechanism for the production of the high energy electrons.

4. Summary

In REPUTE-1 Ultra-Low-q (ULQ) plasmas, the behavior of high energy electrons have been studied with various methods; i.e., the measurements of soft-X ray PHA and Electron Energy Analyzer(EEA), and a low-Z pellet injection experiment. The high energy tail with a strongly anisotropic to the electron drift side has been measured, and a large deflection of the pellet trajectory has been observed. It is also confirmed that the high energy electrons are carrying the dominant part of the plasma current and large fraction of the heat input. Experimental data by EEA measurement and low-Z pellet ablation show the large population of the high energy electrons at the core region in comparison with the edge region, suggesting a MHD dynamo mechanism for the production of the high energy electrons.

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