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# Experiments on selective removal of helium by an application of radio frequency field

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**Abstract**

Proof of principle experiments on preferential removal of helium (He) particles using radio frequency (RF) ponderomotive force have been conducted in linear device (NPX) and tokamak (TXTOR-94). In both experiments, the reduction of the helium ion flux was obtained by applying the RF field at the entrance of the scoop in the pump limiter configuration. The enhancement of helium pumping was observed in the frequency $\omega$ range of $\omega_{\mathrm{CHe}} < \omega < 2\omega_{\mathrm{CHe}}$ where $\omega_{\mathrm{CHe}}$ is the angular ion cyclotron frequency of singly ionized helium ion.
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## 1. Introduction

The control of the helium exhaust is one of the major topics in the fusion programme. The helium pumping performance has been studied in TEXTOR. It was found that a part of helium atoms produced at the neutralizer plate in the pump limiter scoop was ionised by the plasma and flowed back to the scrape-off layer (SOL) [1]. In order to suppress this flow reversal and improve the helium pumping efficiency the method using the RF ponderomotive force (RF-filter) was proposed [2]. The proof of principle experiments for the RF-filter concept conducted in a linear device and a medium size tokamak are presented here. The basic concept used here is the application of the RF ponderomotive force acting on the selected ion. The same concept can be applied for the improvement of the tritium inventory and this can be combined with the improved helium pumping together. The RF field applied in front of the exhaust channel (the scoop) of the pump limiter produces the ponderomotive potential $\Psi_{\mathrm{rf}}$ on the ions $i$ in the charge state $q_i$ and the mass $m_i$ [3,4], which is given by

$$\Psi_{\mathrm{rf}} = \frac{q_i^2}{4m_i}\frac{E_\perp^2}{\omega^2 - \omega_{\mathrm{ci}}^2} + \frac{q_i^2}{4m_i}\frac{E_\parallel^2}{\omega^2}, \tag{1}$$

where $\omega_{\mathrm{ci}}$, $E_\perp$ and $E_\parallel$ are the angular ion cyclotron frequency, RF electric fields perpendicular and parallel to a magnetic field, respectively. If we choose the angular frequency $\omega$ satisfying the condition that $\omega_{\mathrm{CHe}} < \omega_{\mathrm{CT}} \leqslant \omega < \omega_{C\alpha}$ (or $\omega_{\mathrm{CD}}$), $\Psi_{\mathrm{rf}}$ in the first term of Eq. (1) is dominant and that for tritium ($T^+$) and $He^+$ ions are positive, while those for deuterium ($D^+$) and alpha particles ($\alpha$ or $He^{2+}$) are negative. Therefore, if the $E_\perp$ is large enough and localized near the antenna, the tritium can be kept inside the core plasma, while $D^+$ and $He^{2+}$ are introduced into the scoop and the back flow of the low energy $He^+$ can also be suppress by $\Psi_{\mathrm{rf}}$ (Fig. 1).

## 2. RF-filter experiment in NPX

The first experiment proving the RF-filter principle was performed in the linear device NPX. The

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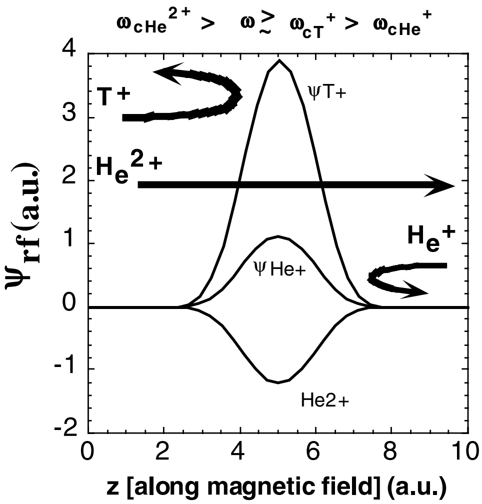


Fig. 1. Ponderomotive potential $\Psi_{rf}$ for tritium ($T^+$), $He^+$, deuterium ($D^+$) and alpha particles ($\alpha$ or $He^{2+}$) ions at $\omega_{CHe} < \omega_T \leqslant \omega < \omega_{C\alpha}$ (or $\omega_{CD}$).

experimental set-up is shown in Fig. 2. The chamber is made of stainless-steel (34 cm in diameter and 230 cm in length) and the uniform magnetic field (within 5% along the chamber) up to 4 kG can be applied. The helium plasmas are produced by an electron-beam which is emitted from a negatively biased oxide cathode ($z = 0$). The beam is extracted through the grounded mesh, where the acceleration voltage, the current density and the beam diameter are 120 V, ~0.6 mA/cm$^2$ and 3 cm, respectively. To simulate the pump limiter, stainless-steel scoop (8 cm in inner diameter and 146 cm in length) is installed in the chamber. At the end of the scoop, the positively biased (100 V) neutralizer plate is placed and the He gas puff is injected from the plate. The pumping duct of 100 cm in length is connected to the scoop end and evacuated by the pump (TMP2) of 160 l/s in pumping speed. The pumping speed for the main chamber (TMP1) is 1500 l/s. For the helium pressure measurement, the Penning gauge is equipped with a spectroscopic set up [5], so that the partial pressure of different gases can be also deduced by observation of their line emission. An antenna to produce $E_\perp$ is 50-turn copper loops (15 cm long along $z$ direction). The antenna surface is placed 4.5 cm from the axis and between 10 and 25 cm outside of the scoop entrance along $z$. The maximum power of RF source is 1 kW at $f = 1.2$ MHz (pulse length = 0.2–1 s). Two cylindrical Langmuir probes, located at $z = 32$ cm and 170 cm are used to measure the plasma parameters. The typical helium pressure during this experiments is $\sim 10^{-4}$ Torr and the RF field cannot produce plasmas in this pressure range.

The reduction of ion flux by the ponderomotive potential is demonstrated. The helium plasma is produced in the scoop by ionizing the puffed gas (3 ms in duration) and flow out the scoop. The reduction of the $He^+$ flow by the RF is measured by the Langmuir probe. The dependence of the ratio of the ion saturation current with RF to that without RF, $\chi$ on the magnetic field strength $B_0$ is shown in Fig. 3(a). The reduction of the ion flux has a maximum at $\omega \sim 1.4\,\omega_{CHe}$. The shift of the optimum frequency higher than $\omega_{CHe}$ and the broadening of the resonance curve can be explained in terms of the collective response of the plasma to the applied RF

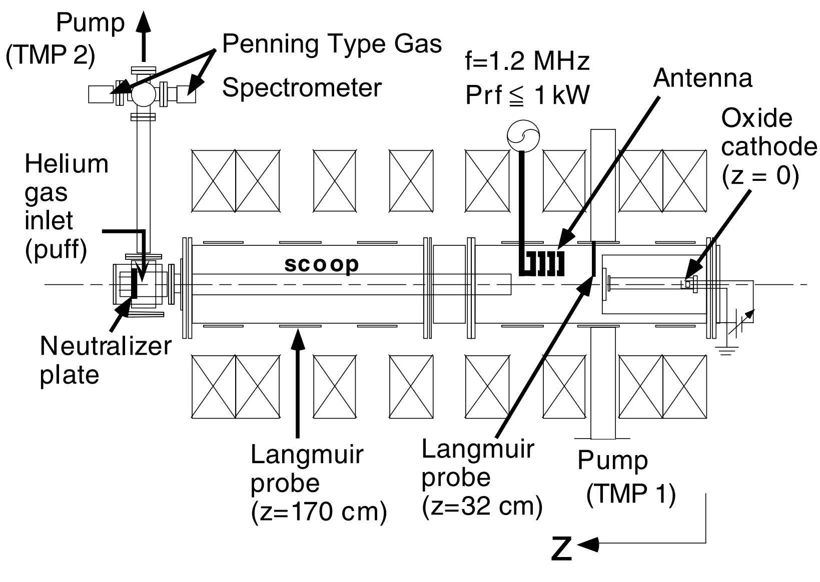


Fig. 2. Experimental set-up of a linear device NPX.

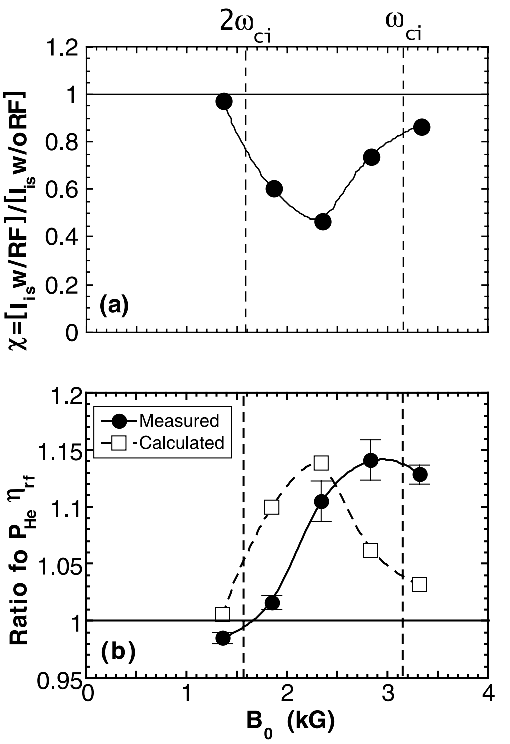


Fig. 3. (a) The dependence of the ratio of the ion saturation current with RF to that without RF at $z = 32$ cm for the helium plasma. (b) The ratio of the increase in the helium pressure by the application of RF to that without RF ($\eta_{rf}$) as a function of $B_0$. $\eta_{rf}$ calculated from Eq. (2) by using obtained in (a) is also shown.

field [6]. The RF electric field in the plasma depends on $\omega/\omega_{CHe}$ and the electron density, $E_\perp = E_\perp(n_e, \frac{\omega}{\omega_{ci}})$, and as a result $\Psi_{rf}$ has a maximum between $\omega_{CHe}$ and $2\omega_{CHe}$ which has been shown in linear device [6]. The reduction of the helium ion flux from the scoop affects the pressure at the head of the pumping duct. The ratio of the increase in the helium pressure by the application of RF to that without RF, $\eta_{rf}$ as a function of $B_0$ is shown in Fig. 3(b). $\eta_{rf}$ has a peak at $\omega \sim 1.1\ \omega_{CHe}$ which is slightly different from that obtained for the reduction of ion flux. $\eta_{rf}$ can be calculated based on the model including the processes: the fraction of the injected neutrals from the target flows to the scoop by $(1-\eta)$. Those neutrals are ionized by the electron beam with the ratio $(1-\exp(-L/\lambda_{ion}))$. Then produced ions are reflected by the ponderomotive potential with the ratio $(1-\chi)$ and come back to the target again, where $\chi = \exp(-\Psi_{rf}/T_i)$. All those factors are multiplied in a single pass and the repeating these processes makes the reduction rate as

$$\eta_{rf} = \frac{1}{1-(1-\exp(-L/\lambda_{ion}))(1-\eta)(1-\chi)}, \qquad (2)$$

where $T_i$, $\lambda_{ion}$, $L$ and $\eta$ are the ion temperature, an ionization mean free path for helium atoms, the length between the neutralizer plate and the scoop opening, and the ratio of the helium flux goes directly to the pumping duct to the one injected from the target. The theoretical curve for $\eta_{rf}$ is in good agreement with the experimental one except near $\omega \sim \omega_{CHe}$. Those results demonstrate some basic proof of RF-filter concept.

## 3. RF-filter experiment in TEXTOR

The RF filter was applied on TEXTOR plasma by using the one of the pump limiter module. The RF antenna of five turn copper loop coil is mounted outside of the scoop under the blade and is directly mounted on the liner (Fig. 4). The entrance of the scoop is open to the ion drift side and the $\nabla B$ drift of ions upward in Fig. 4. The surface of the antenna is about 1.7 cm behind the limiter blade. The maximum RF power is 15 kW at 8 MHz. The antenna length (14 cm in toroidal direction) is short enough not to excite the fast wave at the plasma edge and to produces a localized RF field near the antenna. At the end of the scoop a Langmuir probe is mounted. A Penning ion gauge is installed in the pumping system. The absolute error of the partial pressure measurements are depending on the total amount of injected gas and are typically about 10% for each measurement with and without RF. The helium gas is puffed directly into the scoop of the limiter blade. Depending on the conductance about 50% ($= \eta$) of the helium are directly pumped away. The rest of the helium flows along the scoop where it becomes partially ionised by the incoming plasma flow. The RF field is applied for a duration of 1 s. The electron temperature is between 20 and 50 eV. The local electron temperature in the scoop is about 1.5 times lower than the edge electron temperature measured by thermal beam methods at the same radius. Ohmic as well as neutral beam heated plasmas

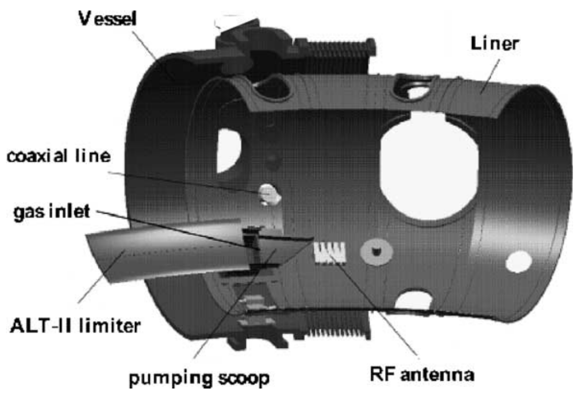


Fig. 4. Schematic view of TEXTOR experiment.

have been applied. The plasma current is 350 kA for all performed experiments. The scoop of the modified limiter blade is opened to the ion drift side.

The toroidal magnetic field is ramped down during a discharge at the RF power level of 3 kW. Fig. 5 shows the increase in the helium partial pressure as a function of toroidal magnetic field strength. The line averaged density of deuterium plasma in this experiment $\langle n_e \rangle$ is $2 \times 10^{13}$ $cm^3$. The He pressure compression at the pump head is observed for a toroidal magnetic field between 2.2 and 1.9 T corresponding to $\omega = 1.15\omega_{CHe} - 1.35\omega_{CHe}$ at the antenna location. It demonstrates the resonance behaviour of the He compression for a frequency range between $\omega_{CHe}$ and $2\omega_{CHe}$ as is shown in the experiment done in NPX. The pressure ratio increases with increasing line averaged density. At a line averaged density of $4.7 \times 10^{13}$ $cm^3$ an increase of 20% is obtained. Additionally the change in the deuterium pressure signal is monitored. Only at very high densities an increase of 2% in the deuterium pressure is measured [7].

The time evolution of the helium and deuterium partial pressures after the helium gas puff is shown in Fig. 6. The pumping speed of helium measured at the duct was decreased when RF is applied while there is no clear change for the deuterium case. The reduction of the pumping speed is attributed to the decrease in the effective conductance of the helium gas at the scoop by the RF plugging effect. These reduction of the pumping speed for the helium by the ponderomotive potential is

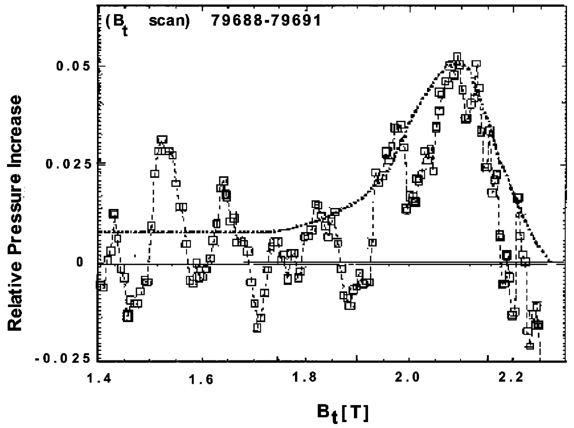


Fig. 5. Relative helium partial pressure change as a function of the toroidal magnetic field.

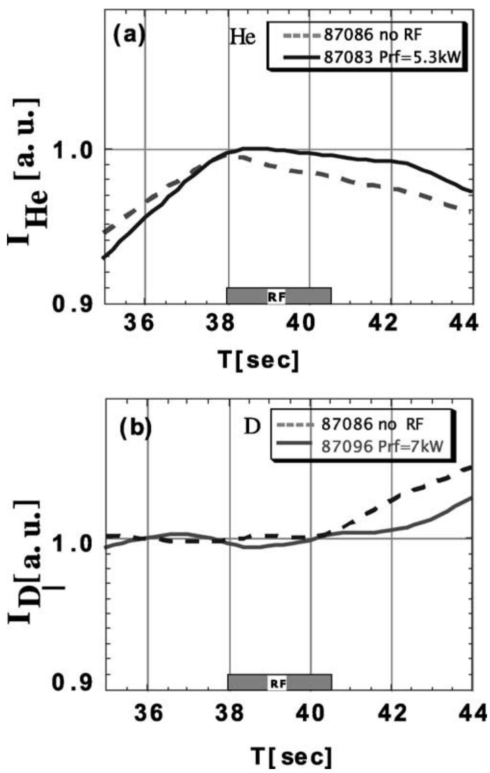


Fig. 6. The effect of RF power on the time evolution of the helium and deuterium partial pressures after the helium gas puff (deuterium plasma).

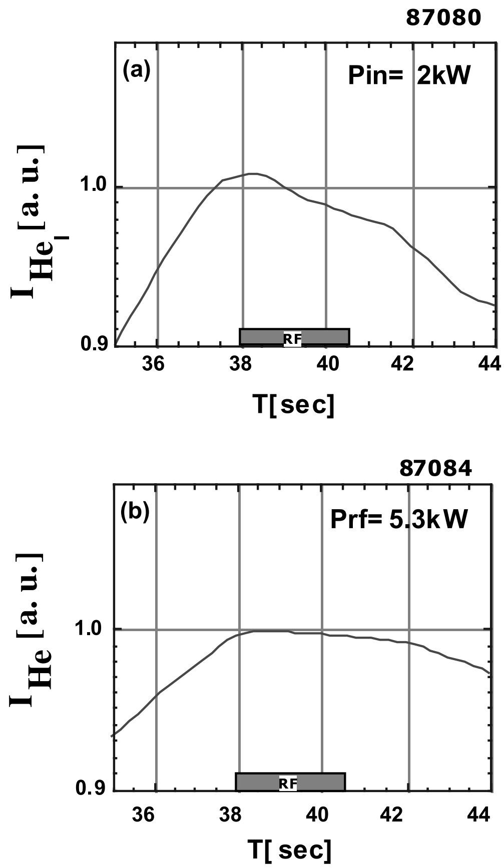


Fig. 7. The time evolution of the helium pressure for different RF powers.

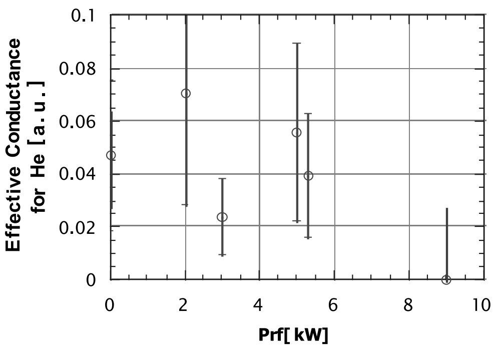


Fig. 8. The reduction of the effective conductance of the scoop for the helium as a function of RF power.

larger for increasing RF power as shown in Fig. 7. The reduction of the effective conductance of the scoop for the helium as a function of RF power is plotted in Fig. 8.

## 4. Conclusions

The experiments in NPX and TEXTOR demonstrate the proof of principle of the preferential pumping of helium in pump limiter configurations. The helium neutrals injected close to the neutralizer plate in the scoop behind the limiter blade are ionized by the low $T_e$ plasma and become $He^+$ with a different mass/charge ratio compared to $D^+$ which comes from the plasma core. Therefore the helium can be filtered separately. A resonance behaviour of the mass/charge selective filter is measured and improvement of He pumping is noticed.

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