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Impurity transport in HL-2A by laser blow-off*

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Among other transient perturbation methods, the laser blow-off injection technique is undoubtedly the best one to study impurity transport because the injection time and the amount of injected material can be controlled in a certain phase of the discharge with a minimum perturbation of the plasma parameters[1]. Furthermore, because the source is of very short duration it provides an experimentally direct measure for impurity transport.

HL-2A tokamak with two closed divertors was constructed in China in 2002. The designed parameters are as follows: major radius R = 1.64 m, minor radius a = 0.4 m, toroidal magnetic field B_t = 2.8 T and plasma current I_p = 480 kA. A system of the impurities injection by the laser blow-off technique was built on this device in 2005. A Nd laser with the pulse of 30 ns and the energy of 10 J was employed. In the first turn experiment several kinds of elements (Al, Ti, Ni) were injected over a wide range of plasma parameters (Ip from 200 to 360 kA, n_e from 1×10^{13} to 4×10^{13} cm^{-3}). The size of the target was 42 mm × 42 mm × 2 mm and the thickness of the metal films was several microns. The impurity target is approximately 710 mm away from the plasma boundary and 130 mm high from the horizontal plane. A VUV spectroscopy measurement on HL-2A device has one line of sight, which focuses on the plasma centre, with the wavelength range from 20 nm to 200 nm. The soft X-ray measurements have five imaging cameras which have 100 channels in total. Its time resolution is 10 μs and spatial resolution is 2.5 cm. Three bolometric cameras have 48 channels in total with the time resolution of 50 μs and spatial resolution of 2.5 cm.

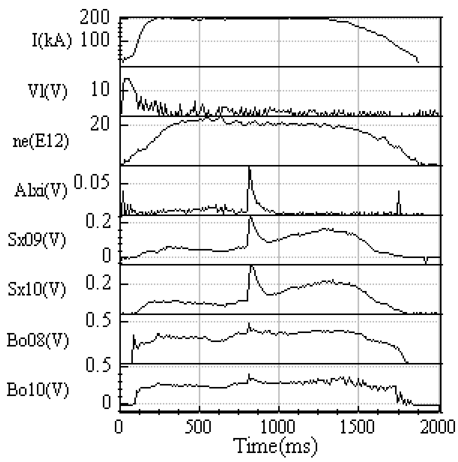

Fig. 1. A typical discharge of the impurity injection for the time evolution of the plasma current, loop voltage, the line averaged electron density, line brightness, soft X-ray signals and bolometric signals.

Figure 1 shows a typical discharge with aluminum injected at 800 ms during the current plateau of which the main parameters are as follows: plasma current I_p = 344 kA,

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toroidal magnetic field B_T = 2.5 T, line averaged electron density $n_e = 0.6 \times 10^{13}$ cm^{-3}. The working gas is hydrogen. In this figure the injection does not disturb plasma current I_p, loop voltage Vl and central line averaged electron density n_e in any noticeable way. However, the signature of the aluminum injection can be clearly seen on the line emission Al xi, soft X-ray Sx09 and Sx10, and bolometric signals Bo08 and Bo10. It means that the parameters of the laser energy and the size of the spot of the impurity were quite compatible for the impurity transport analysis. The electron temperature measured by the ECE heterodyne radiometer is not disturbed obviously in the confinement region.

The expanded soft X-ray signals of several channels at the time of injection are presented in Fig. 2. It is shown that the sawteeth and the reversion sawteeth appear in the centre and periphery region, respectively. After the laser fired at 800 ms the intensities of soft X-ray from the peripheral chords to the central chords increased rapidly. During the rising phase of the signals in the central region the sawteeth became inverted. A jump with the period of about 200us is clearly shown during the inverted sawtooth crash. This implies that there is an inward flow of impurities into the central region when the sawtooth crash. Two inverted sawteeth were observed in this discharge. The first inverted sawtooth was at 805.6 ms. After the second inverted sawtooth, which was at 813.2 ms, the X-ray signals of the central channels reached their peaks. It means that the impurity concentration reaches its maximum in the plasma centre. Then the signal starts to decay as the impurities continuously diffuse out. Similarly, during the decay phase of the signals, the decreasing amplitude at the time of each sawtooth crash is greater than the intensities can be accounted by the temperature drop alone. This also implies that there is an outward flow of impurities from the central region to the outer region during the sawtooth crashes. Each signal can decay to its pre-injection level, indicating the impurity is leaving the plasma on a time scale shorter than the discharge length, with little or no re-cycling.

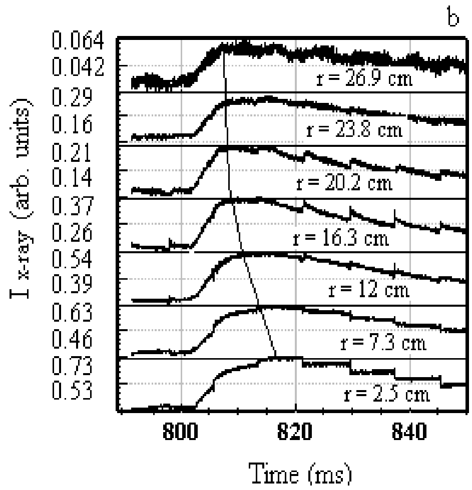

Fig. 2. The time evolution of the expanded view of soft X-ray emission for several chords.

Figure 3 shows the tomographic reconstruction of the soft X-ray emission distributions for the times respectively corresponding to 804 ms(a) and 808 ms(b) in the rising phases, 820 ms(c) and 850 ms(d) in the decaying phases, after the impurity injection. The background level was subtracted. During the quiescent phase of the first sawtooth an hollow emissivity distribution develops as the impurities pile up approximately at 0.16 m from the plasma centre, shown in Fig 3a. After the sawtooth crash, which lasts ~500 μs, there is a significant redistribution of the impurities which causes the peak of the X-ray distribution moving inwards to 0.12 m in Fig. 3b. This means that the convection must be important during this inward movement. After the next sawtooth crash the impurities finally fill up the central region in Fig. 3c. Then the radiation gradually go down with the peaked profile until the impurity disappeared in plasma centre, which is shown in Fig. 3d. The built-up of a hollow emissivity distribution and the slow evolution of the emissivity profile inside the central region between sawtooth crashes also indicate that the impurity transport in the central region of the plasma is much smaller than that in the outside of it.

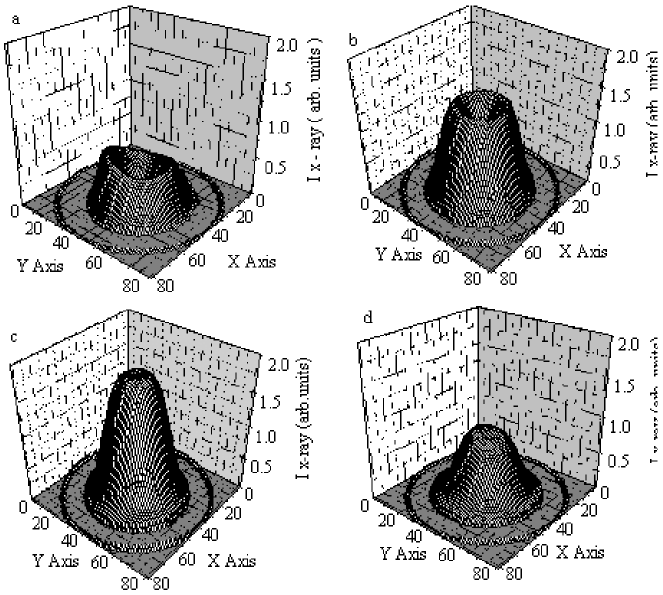

Fig.3. The soft X-ray tomographic reconstruction at several times after impurity injection.

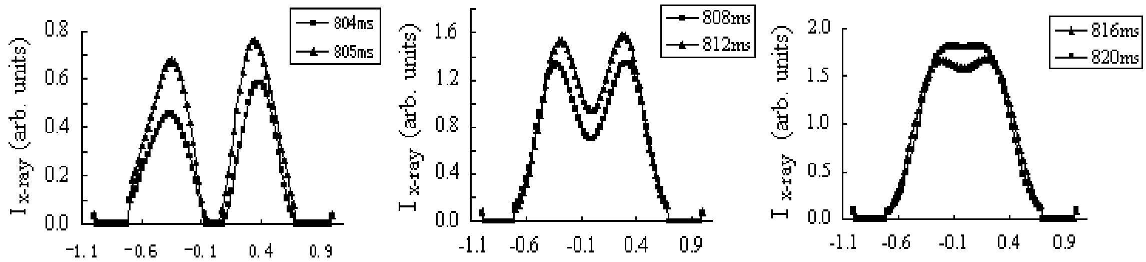

Fig. 4. Soft X-ray emission profiles at several times: a, before the first inverted sawtooth at 805.6 ms; b, before the second inverted sawtooth at 813.2 ms; c, before the third sawtooth at 821.2 ms

In Fig. 4, several soft X-ray profiles are presented to confirm that the inward transport of impurity ions is enhanced during the inverted sawteeth crash. In Fig. 4a, two profiles, which is taken before the first inverted sawtooth, show that the highest density of aluminum ions locate at nearly the same position of r=0.16 m within the calculation error ranges. After the first inverted sawtooth the highest density peak of aluminum ions move to 0.12 m, which are shown in Fig. 4b, and no further inward progression is observed until the second inverted sawtooth. In Fig. 4b, the positions of the highest density peak of aluminum ions between two profiles are almost the same even their interval time is 4 ms. Similarly, after the second inverted sawtooth in Fig. 4c, the high density moves inward further and fill up the centre region at 816 ms. Then the profile is peaked. The enhancement of the impurity transport by the sawtooth crash can be briefly explained by the reconnection of magnetic topology, which is mentioned above.

During the inward movement phase of the injected impurity the transient asymmetric profile of the thermal radiation is observed by the bolometric measurement as shown in Fig. 5. It shows that just before the injection, which is at the time of 800.6 ms, the plasma radiation profile is in a normal shape, being a slight hollow profile. At the time of 801.4 ms the profile becomes strong asymmetry. The peak locates at probably 30 cm of minor radius. The asymmetric profile only sustains in less than 1.6 ms. At the time of 802.2 ms the profile becomes symmetry again and the radiation in the central region increases. Meanwhile the radiation in the out region goes down. After about 20 ms the radiation profile in the out region(r > 0.2 cm) is exactly the same as that before the injection. The difference of the two profiles is only limited in the plasma central region. The observation implies that the injected impurity ions can arrive at 30 cm in a very short time and its profile is asymmetric on a magnetic surface. Then, it becomes symmetric and moves into plasma centre.

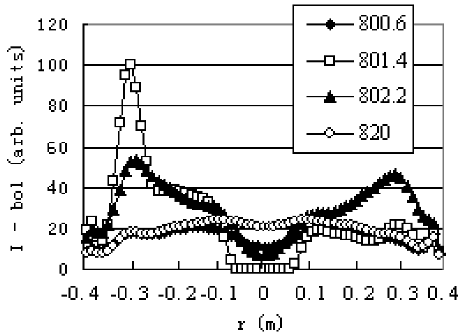

Fig.5. The bolometric profiles after the Abel

In summary, small quantities of medium-Z impurities were injected into HL-2A plasmas by laser blow-off to study impurity transport for the first time. By using the bolometer cameras and soft X-ray cameras the whole inward and outward movements of the injected impurity are clearly obtained. In the very early time and in the outside region of plasma the injected impurity ions have asymmetric profile. Then they propagate into the plasma centre with the symmetric distribution. The tomographic reconstruction of the soft X-ray emission distributions also confirm that the impurity transport is much smaller in the central region of the plasma than outside of it and is greatly enhanced during sawtooth crashes.

References:

[1] Marmar E S, et al. Nuclear Fusion, Vol. 22 (1982) 1567