A SCENARIO OF PULSED ECRH WALL CONDITIONING IN HYDROGEN FOR THE WENDELSTEIN 7-X HELIAS

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A new wall conditioning scenario in hydrogen atmosphere for the Wendelstein 7-X stellarator-helias (W7-X) has been proposed and tested in part. Feasibility of the proposed scenario has been demonstrated on W7-X at OP1.2b experimental campaign during investigation of a chain of ultra-short pulsed electron cyclotron resonance heating plasma discharges.

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INTRODUCTION

The hydrogen wall conditioning aiming for producing hydrogen atoms was practiced at many fusion devices with true positive results [1, 2]. It is efficient especially for removal of hydrocarbons and reduction of oxide layers that are adsorbed in the vacuum chamber. The application of such H_2 wall conditioning in W7-X is aimed at improving the performance of the powerful discharges and widening the operational window. Wall conditioning in hydrogen relies upon production of hydrogen ions and atoms in plasma that can interact chemically with the impurities adsorbed at the wall. It is applied on W7-X through standard glow discharge conditioning after opening vacuum chamber to air. During the regular operation cycles, in presence of the magnetic field, it may be applied through an RF discharge, where the atoms are expected to play a major role in the interaction on surfaces that are inaccessible to plasma ions.

The discharges generate low energy hydrogen atoms which do not contribute much to wall pre-loading. To produce atomic hydrogen neutrals H^0 efficiently, sufficiently dense plasma is necessary. However, for the the desorbed impurities to be pumped, but not ionized, the plasma density should be low. To keep the production rate of H^0 atoms high, the neutral gas pressure should be as high as possible. In ECRH discharge the plasma density lower margin is determined by ECRH shine through. The upper level of the pressure is given by the break-down condition. Since plasma is dense, the probability of ionization of impurities desorbed from the wall is not small for the Electron Cyclotron Wall Conditioning (ECWC).

The solution could be a periodic pulsed discharge which gives some idle periods of time to pump the outgassed impurities [3]. Such discharge is practiced at W7-X (pulse trains to condition the divertor [4]), but the pulses are long compared to plasma production time and the plasma is hot and fully ionized. The aim of the proposal is to study the regime of ultra-short ECRH pulses that produce partially ionized plasma in the atmosphere of hydrogen.

The numerical experiments [3] have shown that for the reason of good charged particle confinement in the stellarator, the discharge tends to produce dense plasma with low electron temperature. During plasma production the plasma temperature decreases, the level of atomic hydrogen generation reduces. The major part of the power goes to the inelastic collisions that produce vibrational and rotational excited states of molecules that are de-excited after collisions to the vacuum chamber wall and, therefore, do not contribute to the dissociation and atomic hydrogen production. This could be avoided by increase of the input power, but the plasma density misbalance will result in the rapid density rise. For this reason the discharge should be pulsed. The electron temperature during the pulse can be controlled and established favorable for H^0 generation.

In the dead time between pulses the plasma density decay is provided by the dissociative recombination of the molecular ions. In this process the atomic hydrogen is also generated.

EXPERIMENTAL CONDITIONS

The elements of the proposed scenario are investigated using time slots between the regular discharges of the W7-X. Therefore, in the experiments, the regular discharges with duration about 5 s were used as a pre-ionization tool. These were low-quality discharges from the plasma confinement point of view and the majority of them ended up with a radiation collapse during experiments under consideration. Nevertheless, they are suitable for pre-ionization.

In order to monitor plasma parameters during the wall conditioning discharges and to obtain preliminary estimates, the data from the following W7-X diagnostics [5] were used:

- QSR02 Filter Scopes (H Alpha);
- QSR - H alpha Diagnostics (H-alpha Cameras);
- QMJ - Single Channel Dispersion Interferometer for line-integrated electron density (IED);
- QSD - HEXOS (High Efficiency XUV Overview Spectrometer).

In Fig. 1, line averaged electron plasma density evolution for two of successfully realized pulse plasma discharges is shown: single-pulse (see Fig. 1,a) with 3 ms duration and four-pulse discharge (see Fig. 1,b) series of the same pulse duration made after shut down of the regular discharge. Both of them have produced plasma with sufficient density; see plasma density spikes at the ends of the discharges.

One of the most important parameters the proposed pulse discharges depends on is the time interval between the end of the base discharge and the beginning of the first pulse. The 0.9 s time delay occurred to be suitable. Another important parameter in the case of consequent multiple plasma pulses series is the time interval between pulses. In our case, the 0.3 s delay was appropriate to have a sufficient pre-ionization before each pulse for effective operation in the multiple pulses regime.

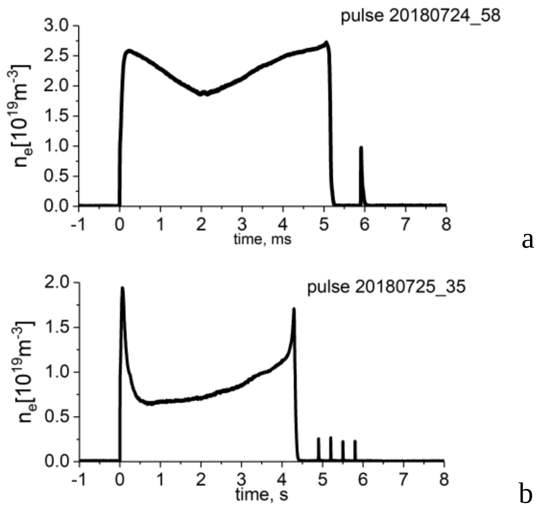

Fig. 1. Average electron plasma density evolution in the proposed scenario with one (a) and four (b) pulses

Two types of discharges have shown a similarity of plasma properties during both single and multiple pulse discharges according to a comparison of available diagnostics measurements.

EXPERIMENTAL RESULTS

Applicability of the proposed scenario should be experimentally confirmed by the following points: (i) a well-controlled production of low temperature and partially ionized plasmas for H^0 generation in reactions accompanied by dissociation; (ii) sufficient amount of H^0 produced all over the W7-X confinement volume during pulse discharges; (iii) an evidence of decrease of outgassing of the vacuum chamber wall; (iv) general improvement of the regular W7-X operational mode characteristics.

During the experiments described here, the item (i) and partially item (ii) have been successfully confirmed, as described below.

Let us discuss the W7-X plasma discharge #20180724.58 with a single pulse after 5-s pre-ionization, Figs. 1-3. Plasma with lower, as compared to the preceding regular discharge, density is produced during the pulse (see Fig. 1,a). The electron temperature was registered using the QME – Electron Cyclotron Emission diagnostics. Its value attains $T_e \sim 1$ keV during the ECRH power injection. A higher time resolution that would allow one to trace its exact evolution during the short plasma pulses was not available. The indirect evidence of a sufficient T_e is the presence of H_α intensity registered with QSR02 Filter Scopes (Balmer series, Fig. 2) and HEXOS (Lyman series, the same figure), as well as impurities emission lines registered with HEXOS. Hence, necessary conditions for atomic hydrogen generation are provided.

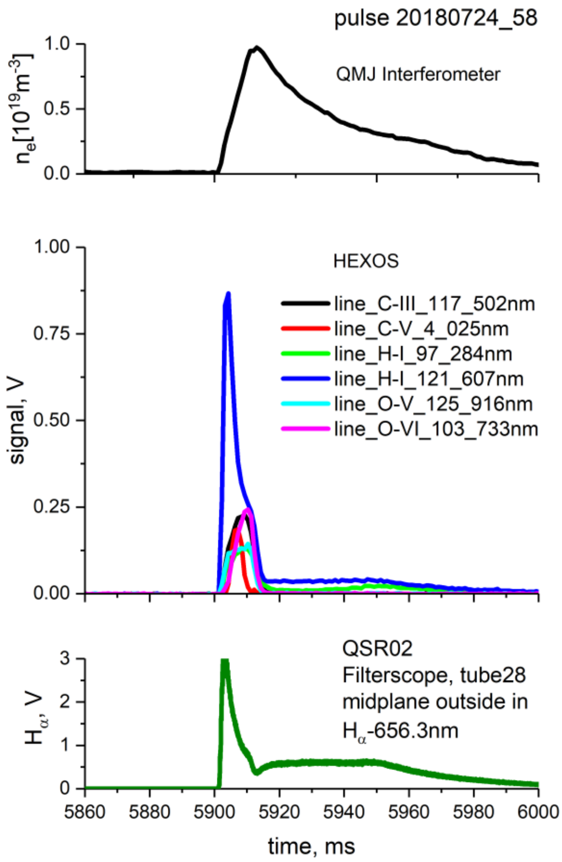

Fig. 2. Electron plasma density (upper chart), various emission lines registered with HEXOS (in the middle) and QSR02 Filter Scopes (bottom)during the single pulse discharge

An important feature of efficient cleaning discharge is an isotropy of its cleaning ability across the whole vacuum chamber. The H-alpha visible spectroscopy camera (QSR – H-alpha Type 2 Cameras, Fig. 3) indicates volumetric plasma production during pulses, and consequently generation of H^0 should take place all over the confinement volume.

Juxtaposition of plasma density and H_α emission intensities evolution (see Fig. 2) reveals the delay of density maximum relative to the maxima of H_α. A suggestion can be made that with an ECRH power injection, a significant amount of high-temperature electrons is produced. Since their temperature is high, 1 keV, each such electron can make 10…20 ionizations. However, the plasma density increases less after ECRH end, only in 5 times. Then the hot electrons are not in majority in such a plasma. Following CV carbon line behavior (see Fig. 2), the hot electrons are thermalized in 10 ms and, after this, plasma density rise stops. Finally, the plasma decays relatively quickly, that indicates about a prevalence of recombination processes over diffusive ones. Such plasma discharge dynamics provides favorable conditions for the atomic hydrogen generation.

In order to check presence of an atomic hydrogen generation process during the pulses, one can apply a well-known approach to hydrogen Lyman or Balmer spectral series analysis [6].

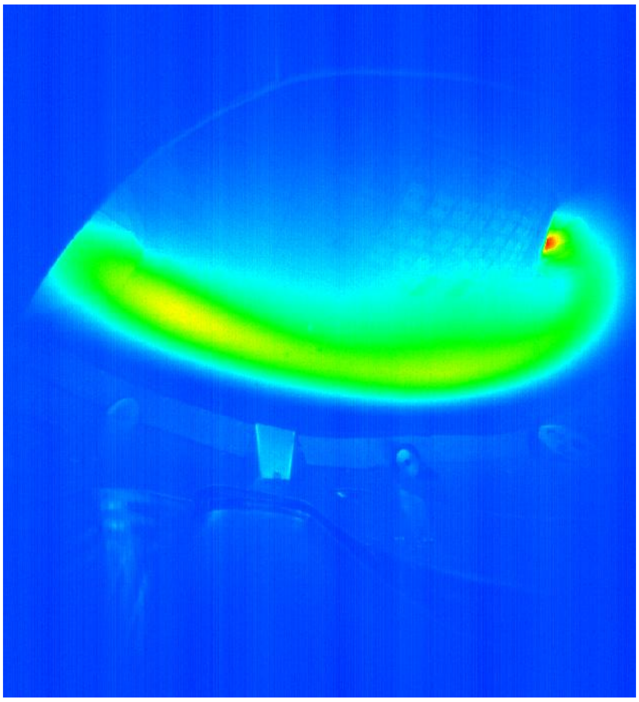

Fig. 3. QSR - H-alpha Type 2 Camera during the single pulse discharge

The Balmer series intensity registered with QSR02 filter scope have allowed one to analyze atomic hydrogen generation during single-pulse discharge, as shown below.

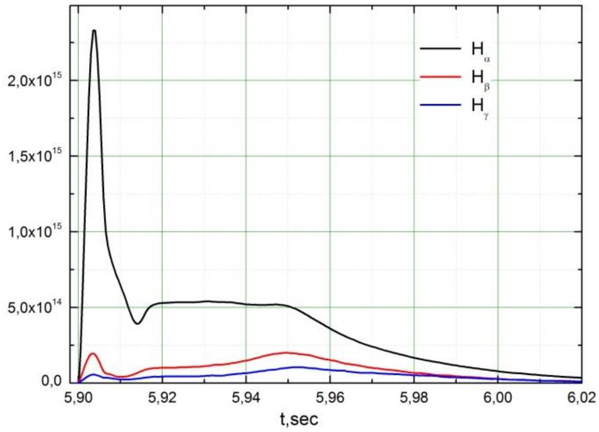

Fig. 4. QSR02: H_α, H_β, and H_γ time evolution in the single pulse discharge

From the measured absolute values of the intensity of the spectral lines of the Balmer series for the atomic hydrogen (H_α, H_β, H_γ in Fig. 4), the dependences of the relative population of the excited atoms in the levels at different phases of the cleaning discharge (Fig. 5) are calculated using Einstein coefficients [7].

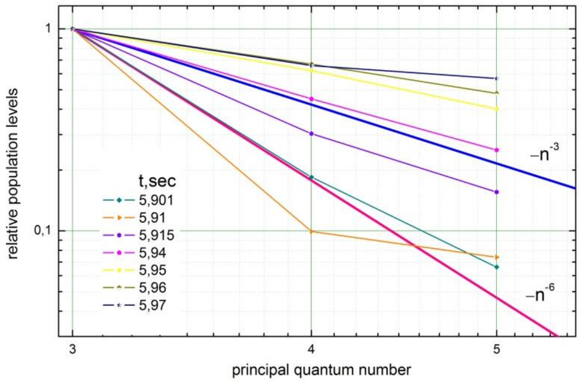

Fig. 5. Calculated relative population levels of excited hydrogen atoms

From the calculated dependences, it can be seen that the active phase of the discharge and 10ms after it, the population of the excited states of hydrogen atoms is completely due to the dissociation of molecular hydrogen – the curves lie in the ~ n^{-6} dependence [5] (n is the principal quantum number). The plateau region in H_α in Fig. 4 appears to be a transition from dissociation to recombination and involves probably both of these processes since curves group around the line n^{-3}. And from the time moment 5.950 s there is domination of the pure atomic recombination: the curves go higher than line n^{-3}.

SUMMARY AND CONCLUSIONS

The scenario of short-pulse ECRH discharges series in hydrogen had been proposed for wall conditioning in W7-X. In the beginning of the W7-X experimental campaign OP1.2b, successful discharges were produced in accordance to the proposed scenario, with a single and four ECRH pulses start-ups with use of a pre-ionization plasma:

1. A single ECRH pulse of 3 ms duration creates plasma of half density compared with preceding full-scale pulse ended 0.9 s before.
2. There are indications that the plasma is not fully ionized (optical lines behavior, half plasma density), and the atomic hydrogen intensive generation is expected.
3. Plasma decay is quite fast compared to the diffusion rate. It is rather recombination-like than diffusive. This allows one to use high repetition rate (5 Hz).
4. The H-alpha visible spectroscopy camera indicates volumetric plasma production during pulses.
5. The analysis of Balmer series of hydrogen optical lines point out the dissociation and recombination stages of the discharge.
6. A chain of 4 pulses accompanied with gas puff is successful. Such a chain may be a base for an ECWC scenario.

Thus, the feasibility of the proposed scenario implementation has been confirmed. A full elaboration of the optimal atomic hydrogen-based scenario for the wall conditioning using an ECRH in W7-X is planned.

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СЦЕНАРИЙ ИМПУЛЬСНОЙ ЭЦРН ЧИСТКИ СТЕНКИ КАМЕРЫ В АТМОСФЕРЕ ВОДОРОДА ДЛЯ ХЕЛИАСА WENDELSTEIN 7-X

В.Е. Моисеенко, А.А. Белецкий, А.Н. Шаповал, T. Wauters, A. Goriaev, K.J. Brunner, B. Buttenschön, P. Drewelow, V. Winters, R. Brakel, A. Dinklage, S. Brezinsek, T. Stange, H. Laqua, S. Lazersson и команда W7-X

Был предложен и испытан новый сценарий кондиционирования стенки в атмосфере водорода для стелларатора-хелиаса Wendelstein 7-X (W7-X). Использован принцип кондиционирования стенок камеры атомарным водородом, производимым в плазме, который химически взаимодействует с примесями, адсорбированными на поверхности камеры, обращенной к плазме. Возможность реализации предложенного сценария была подтверждена на W7-X во время экспериментальной кампании OP1.2b при изучении цепочки ультракоротких импульсов в плазме с нагревом в условиях электронного циклотронного резонанса.

СЦЕНАРІЙ ІМПУЛЬСНОЇ ЕЦРН ЧИСТКИ СТІНКИ КАМЕРИ В АТМОСФЕРІ ВОДНЮ ДЛЯ ХЕЛІАСА WENDELSTEIN 7-X

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Був запропонований і випробуваний новий сценарій кондиціонування стінки в атмосфері водню для стеларатора-хеліаса Wendelstein 7-X (W7-X). Застосовано принцип кондиціонування стінок камери атомарним воднем, виробленим в плазмі, який хімічно взаємодіє з домішками, адсорбованими на поверхні камери, зверненої до плазми. Можливість реалізації запропонованого сценарію було підтверджено на W7-X під час експериментальної кампанії OP1.2b при дослідженні ланцюжка ультракоротких імпульсів з нагріванням за допомогою електронного циклотронного резонансу.