Plasma Performance Improvement with Neon Gas Puffing in HT-7

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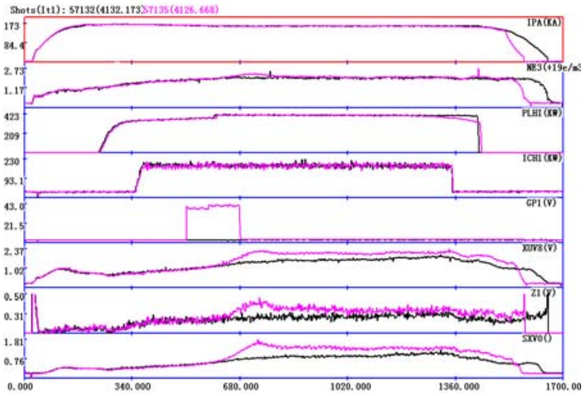
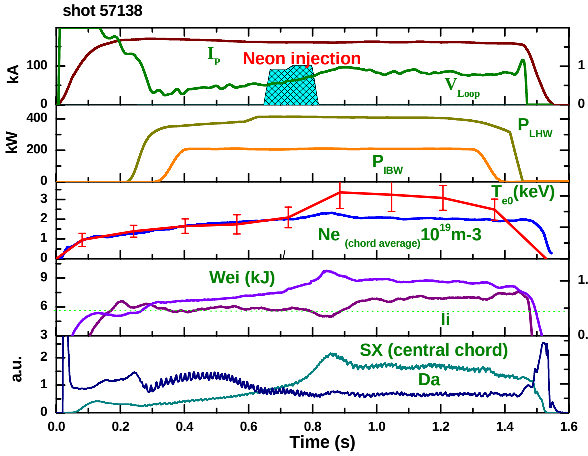
Abstract. The neon gas puffing for the production of a radiative layer near the plasma edge with the improved energy and particle confinement has been investigated in HT-7 during the 2003 campaign. Plasma characteristics of these discharges in HT-7 are similar to the TEXTOR RI–mode discharges. The peaked electron temperature and the broadened density profiles were formed in these discharges with the combination of LHCD and IBW heating. The central electron temperature was increased by nearly 50%, compared those discharges with the same plasma parameters and injected power without the neon gas puffing. These discharges also exhibited relatively higher plasma inductance.

1. Introduction

Radiative Improved mode (RI-mode), with high radiating power fractions and energy confinement enhancements over ITER89-P L–mode scaling, is an attractive operating scenario for future fusion ignition plasma devices. This confinement mode has been extensively studied on TEXTOR, and has been successfully demonstrated by seeding a well-chosen (small) amount of Ar, Ne or Si in the plasma edge [1,2]. The very promising results of radiative mantle plasmas in TEXTOR-94 have been recognized worldwide, and currently nearly every tokamak is trying to reproduce these. Operational regimes with reduced anomalous transport resulting from seeding of impurities were obtained in different tokamaks, e.g., in ISX-B, ASDEX-U, FTU, DIIID, JET, JT-60U [3,4,5,6,7].This improved confinement mode does not depend either on the magnetic configuration (limiter or divertor, circular or elongated cross section), or on the plasma heating method (ohm, neutral beam injection, or ion cyclotron frequency heating). The RI-mode has many advantages with respect to other modes of improved confinement (1) It can be maintained up to density limit, and in some cases also beyond this limit; (2) it can be free of MHD instabilities, when β is below the critical value, and thus is not transient (it last many energy confinement times on TEXTOR); (3) it is characterized by a large radiation emission from the injected impurities: up to 90% of the total input power can be radiated, thus strongly alleviating the heat load problem on the first wall materials; (4) it is compatible with the H-mode, since it even improves the H (= τ_e/τ_{e-L}) value in this regime.

Detailed measurements on the DIII-D tokamak have shown that the presence of the impurity significantly damps plasma turbulence. Furthermore, by careful deuterium fuelling, it has been possible to reach ELM free H–mode confinement quality at 1.4 times the Greenwald limit n_{Gr}, i.e. far beyond what was previously thought to be an ultimate density limit on tokamaks. These discharges reach high-normalised beta values β_N of 1.8, close to the beta-limit of the device (β_N=2) with radiating powers in the mantle up to several MW, for durations larger than 20 energy confinement times. [8,9] More in particular, on the 2 largest tokamaks in the world, JT-60U and JET, the following has been obtained recently:(a) On JT60-U ELMy H–mode plasmas have now been realized at densities up to n/n_{Gr} ~65% with Ar as radiating impurity, whereas without impurity high confinement is reached only up to n/n_{Gr} ~ 40%. (b) On JET, also with Ar seeding, outstanding combinations of density and confinement have been realized (f_{H97} =1, n/n_{Gr} = 90%) and this for 8 confinement times or nearly 3 seconds.





(a) (b)

Fig. 1(a) Time traces for typical discharges without (#57132 black) and with (#57135 red) neon gas puffing in HT-7: plasma current, central line average density, total input power (LHW&IBW), gas fuelling rates, radiated power (central chord), central line average bremsstrahlung emission, central SXR emission

Fig. 1(b) Temporal evolution of plasma current Ip, heating power, central electron temperature Te, central line average density ne, plasma energy Wei, inductance li, intensity of soft-X ray (central chord), Da emission with neon gas puffing discharge in HT-7.

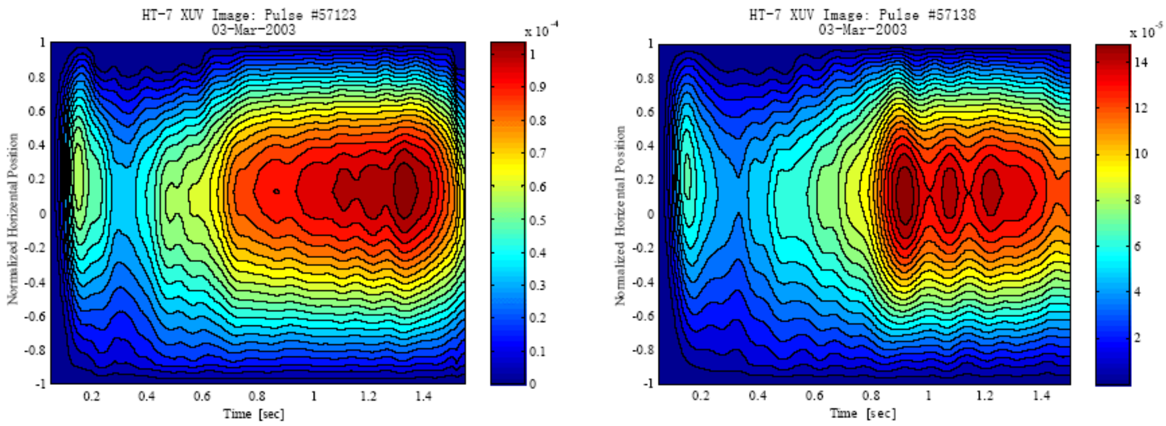


Fig. 2 The XUV image of HT-7, the profile of the radiated power with (#57138 right) and without (#57123 left) neon gas puffing

2. Experiments with neon gas-puffing in HT-7

HT-7 is a medium sized superconducting tokamak with limiter configuration. New doped graphite with a SiC gradient coating is chosen as poloidial and toroidial limter materials with actively water-cooling. Its main purpose is to explore higher performance plasma operation under steady-state conditions and relevant physics [10]. As a result, the longest pulse discharge with a central electron temperature $T_{e\ (0)}$ ~ 1.0 keV and a central density $n_{e(0)}$~$0.8\text{x}10^{19}$ m^{-3} almost steady-state conditions was obtained with a duration of over two handred seconds. The machine is normally operated with plasma current Ip = 150~250KA, toroidal magnetic field Bt = 1.75~2.0T, central line-averaged density $1.0–3.0\times10^{19} m^{-3}$, and with a R=1.22m major radius and a=0.28m minor radius. The machine is equipped with lower hybrid wave current (LHCD) system and an ion cyclotron resonant heating (ICRH) system.

The ICRF system with 350KW in the frequency range 18–30MHz can be launched directly in the scheme of an IBW mode. The LHW system with 1.2MW power at a frequency of 2.45 GHz can be operated in CW mode. The experiments presented in this paper were carried under the condition of an ICRF boronized wall [11,12]. The neon gas puffing for the production of a radiative layer near the plasma edge with the improved energy and particle confinement has been investigated in HT-7 during the 2003 campaign. By careful deuterium fuelling, plasma discharges characteristics in HT-7 are similar to TEXTOR RI–mode discharges compared with the TEXTOR RI–mode scaling relation. Waveforms for typical discharges without and with impurity seeding are compared in Fig. 1(a). There are the almost same auxiliary heating power with LHCD and IBW (P=0.7MW), central line average density ($ne=2.0x10^{19}m^{-3}$), plasma current (Ip=160KA), and toroidal magnetic field (Bt=2.0T). Radiated power can be seen to rise steadily after neon injection, but the central line-average bremsstrahlung emission and soft x-ray (SXR) emission show similarly prompt increases suggesting its rapid permeation across the entire plasma. The more broadened profiles of radiative power in Fig.2, shows that the radiating mantle is formed more close to the plasma edge at around r/a~0.6. The total radiative power is increased up to 60% after neon gas puffing with the same experimental condition.

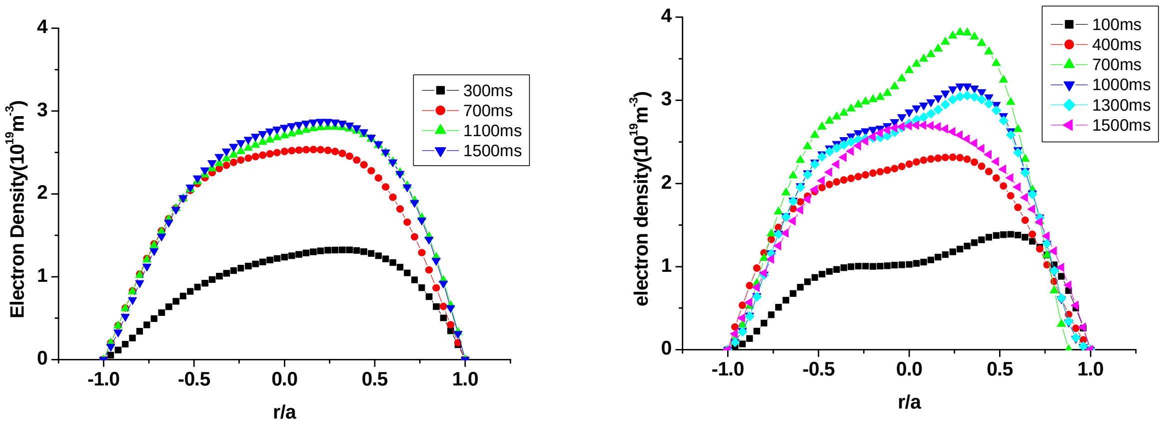
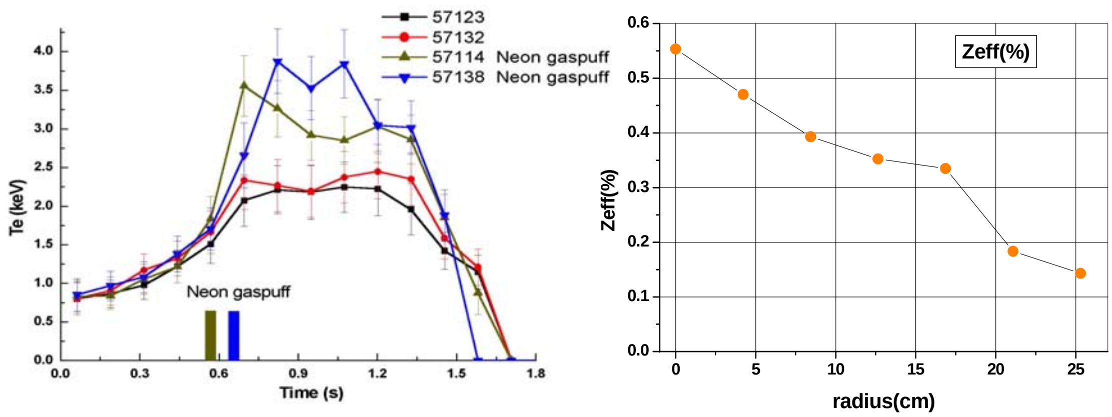


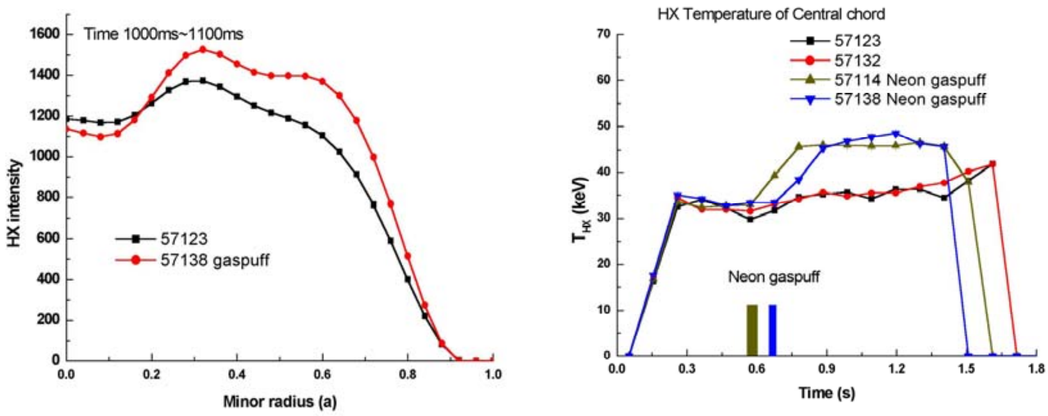
Fig. 3 The electron density profiles at different time, discharge with (#57138 right) and without (#57123 left) neon gas puffing.



(a) (b)

Fig. 4(a) The central electron temperature for reference discharges without neon seeding (#57123 #57132) and with neon seeding (#57138 #57114), measured by SX-PHA.

Fig. 4(b) The effective ion charge, Z_{eff}, changes between 550ms(before neon injection) and 850ms(after neon injection) for shot #57138.



(a) (b)

Fig.5(a) The profile of HXR at 40-60Kev in reference plasma without neon gas puffing (#57123) and with neon gas puffing plasma (#57138).
Fig.5(b) The intensities of the central HX emission, in reference plasma without neon impurities injection (#57123, #57132) and with neon gas puffing plasma (#57138, #57114).

3. Plasma performance with neon gas puffing

During discharges with the neon gas puffing, plasma with the performance of $\beta_N H_{89}$ >1 has been obtained for several tens of energy confinement times in HT-7.The temporal evolution with neon gas puffing discharge is depicted in Fig.1 (b); the improved confinement phase started shortly after neon injection. The reference discharge is also shown in Fig.1 (a). The central line-averaged electron density was about $2.0x10^{19}m^{-3}$, with unchanging before and after neon impurities injection, because the electron density feedback by deuterium (work gas) fuelling was performed in HT-7, but the wider density profiles were formed shown as in Fig.3. At the peak position of electron density profile, the radiated power fraction increases to 0.5 or more with neon seeding. From peaked electron temperature formed in these discharges with the combination of LHCD and IBW heating, it can be seen that the central electron temperature was increased by nearly 50%, compared those discharges with the same plasma parameters and injected power without the neon gas puffing (Fig.4(a)). The storage energy and particle confinement time are increased for discharges with neon gas puffing, and also exhibit a drop in edge electron temperature immediately after the initial neon gas puffing. This latter phase is characteristic of the TEXTOR RI–mode with best operation to date in sawtooth discharges.

The plasma stored energy and plasma internal inductance are displayed in Fig.1 (b), was provided by the combination of a diamagnetic loop and a poloidal array of poloidal and radial magnetic probes. Although the stored energy is partly contributed from the increment of OH input power, it does not lead to the degradation of the plasma confinement. Furthermore, the core plasma confinement is improved from the integral of the peaked electron temperature and the boarded electron density. These discharges also show relatively higher plasma inductance compared with the reference discharges without the neon gas puffing, suggesting that seeding of impurities injection might be compatible with the advanced tokamak operation region for the higher inductance. The profile of the effective ion charge, Z_{eff}, measured by bremsstrahlung emission (seven channels), was changed between 550ms(before neon injection) and 850ms (after neon injection) for shot #57138, during neon injection discharge as shown in Fig.4(b). While such an increase in Z_{eff} raises the central P_{brem}, one should note that the important reactor quantity is $P_{brem} / P_{\alpha} \propto Z_{eff}$ ($f^{2}_{DT} Te^{1.5}$). An increased Z_{eff} and dilution is compensated by the concomitant RI-M confinement improvement, which allows achieving at the same density a strongly increased electron temperature.

The intensities of the central HX emission, with neon gas puffing in the IBW heated and LHCD plasma (#57138, #57114), were increased significantly, which are partially due to the increase in the electron density and effective ion charge. The increment of the HXR at half minor radius was more prominent than at the central viewing line, implying a broadened HXR profile. The profile of at energy of 40–60 KeV is also shown in Fig.5, during 1.0s~1.1s for shot #57138 with neon injection and the shot#57132 without neon injection. When the gaseous impurities are injected into the plasma in a controlled way by gas puffing, the average charge of ions increases. Neon impurity concentrations in these discharges were of order 1%, producing only a moderate increase in Z_{eff}. These increase quench the growth rate of the ion temperature gradient (ITG) instability, and thus decreases substantially the particle diffusion coefficient [5,6]. As a consequence the outward particle flux decreases, causing the peaking of the density profile. This further quench (or even suppress) the ITG mode, mainly in the outer part of the plasma volume, with a resulting increase of both the particle and energy confinement. Transport code has been used to calculate thermal diffusivity, decreasing dramatically over most of the profile with neon gas puffing, which is in the region where the ion temperature gradient is increasing. Within the region of higher temperature gradient, plasma thermal pressure is generally higher than the reference discharge, consistent with the lower transport in the neon seeded discharges.

4. Summary

The neon gas puffing for the production of a radiative layer near the plasma edge has been investigated in HT-7. In these experiments a deliberate pollution of the plasma led to an improvement of the confinement in spite of increased radiation losses, the plasma with the performance of $\beta_N H_{89} > 1$ has been obtained. From the peaked electron temperature and the broadened density profiles formed with combined LHCD and IBW heating, the central electron temperature was increased by nearly 50%, with the same plasma parameters and injected power. These discharges also exhibited a relatively higher plasma inductance compared with the reference discharges without the neon gas puffing. Future experiments are planned to extend operation to higher densities ($ne/n_{GW} \approx 1$), including extending RI–mode to higher normalized parameters, for long pulse higher performance discharges in HT-7, it is characterized by a large radiation emission from the injected impurities, creating a cold radiating mantle at the plasma boundary, thus strongly alleviating the heat load problem on the first wall materials, impurity seeding can help power exhaust problems, it is important for future tokamak reactor like as ITER.

Acknowledgment

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