Radiative divertor experiments with Ar and Ne seeding on EAST

Jingbo Chen[1,2], Yanming Duan[1], Zhongshi Yang[1]*, Liang Wang[1], Kai Wu[1,2], Fang Ding[1], Hongmin Mao[1], Jichan Xu[1,2], Ling Zhang[1], Jinhua Wu[1], Marco Wischmeier[3], Lingyan Xiang[1,3], Sven Wiesen[4], Guang-Nan Luo[1], and EAST Team[a]

[1]Institute of Plasma Physics, Chinese Academy of Sciences, P.O. Box 1126,Hefei, 230031, China
[2]Science Island Branch of Graduate School, University of Science & Technology of China, Hefei, China
[3]Max Planck Institute of Plasma Physics, D-85748 Garching, Gemany
[4]Forschungszentrum Jülich, Jülich, Gemany

Abstract

Radiative divertor experiments with Ar and Ne seeding have been carried out during recent EAST experimental campaigns. The results proved the high efficiency of Ar and Ne in reducing heat load and particle flux onto the divertor target. However, core plasma contamination and PFCs sputtering were observed with Ar seeding especially when the impurity was seeded from upper tungsten divertor. The experiments with different seeding pulse width proved Ar is a strong radiator for EAST, and excessive Ar seeding easily caused the burst of radiation in the plasma core region which led to a great loss of plasma stored energy. To compare with Ar seeding, Ne seeding experiment was carried out in EAST 2016 spring campaign. Its preliminary results showed Ne, compared with Ar, has advantages on radiation profile and less contamination in plasma core region.

1. Introduction

Increasing divertor radiation by injecting impurities is a general and effective method to reduce heat flux from scrape-off layer and to cool the divertor plasma to detachment. Impurities such as nitrogen (N_2), neon (Ne) and argon (Ar) have been widely used in radiative divertor experiments on several tokamaks. In ASDEX-Upgrade, in full tungsten divertor wall condition, complete and partial detached plasmas were achieved by feedback controlled N_2 seeding. In addition, Ar or Ne impurities were also used to control the heat flux onto the divertor successfully [1, 2]. In JET, N_2 seeding is used to compare the effect of reducing heat load on ITER-Like wall (ILW) to all-carbon wall conditions. N_2 seeding elicits different responses between them in raising plasma density, reducing ELM frequency and pedestal pressure [3]. In JT-60U, with Ne, Ar and a mixture of Ne and Ar injection in H-mode plasmas, the fractions of divertor radiation power by these impurities in addition to an intrinsic impurity, C, were investigated. It was found that Ne is the biggest radiator when plasma detached by Ne seeding but carbon acts as the biggest radiator with other impurities seeding in carbon wall condition [4].

Owing to the routine lithium wall coating conditioning before EAST discharges, Ar, instead of N_2, is used as the seeded impurity to achieve long-pulse high-performance operations in EAST [5-7]. In this work, the radiative divertor experiments by using the mixture of Ar/D_2 (1:4) as seeded impurity carried out during EAST 2014 and 2015 campaigns were introduced with more details in subsequent sections. Furthermore, EAST has upgraded its upper divertor into actively-cooled W/Cu plasma-facing components (PFCs) in 2014[8]. In recent discharges, excessive Ar seeding easily caused the contamination in core plasma region. Despite a reduction in electron temperature and power flux, Ar injection had led to a significant increase of the sputtered tungsten flux near the strike point, especially when the impurity was seeded from upper tungsten divertor target, which is discussed in section 3. Section 3.2 describes the differences of using long and short pulses for Ar seeding in upper single null (USN) divertor configuration. To compare with Ar seeding, Neon was used as the radiator in 2016 campaign. Its preliminary result will be shown on Section 3.3. Summary and future plan are presented in the last section.

2. Experimental setup and relevant diagnostics

During EAST 2014 and 2015 campaigns, radiative divertor experiments were carried out in L-mode discharges and H-mode discharges in order to compare the differences between these two confinement modes in distribution of heat load reduction, asymmetry and impurities behaviors in divertor region. As shown in Fig. 1, the controlled pulsed mixture of Ar/D_2 (1:4) was injected through a pipe located inside the

*Corresponding author: Zhongshi Yang (zsyang@ipp.ac.cn)
[a]See Appendix of B. N. Wan et al., Nucl. Fusion 55, 104015 (2015)

divertor target near the strike point. The delay time of Ar affecting on plasma was about 75ms-140ms limited by the length of pipes after the upgrade of divertor gas puff system in 2014[9]. Width of puffing pulse followed the PCS (plasma control system) program setting. According to lower single null (LSN) and upper single null (USN) configuration, the mixture was injected from different regions, i.e., lower carbon divertor and upper ITER-Like tungsten divertor, in several discharges. The results are discussed in section 3.

Information on electron temperature, electron density, and particle & heat flux on divertor targets can be provided by EAST divertor Langmuir probe diagnostic system[10, 11] consisting of 89 groups of triple probes of which the poloidal layout is shown in Fig. 1. The total and the profile of radiated power in bulk plasma can be provided by four 16-channels AXUV (absolute extreme ultraviolet) arrays, total 64 channels, installed in P horizontal port, and one 24-channels AXUV array, installed in the up-vertical C port[12]. Impurities, such as argon, neon, deuterium, lithium carbon, and tungsten, in upper divertor region (only inboard and outboard targets) can be observed by divertor tungsten spectroscopy with the range the range of 399-431 nm. These results have been also confirmed by a flat-field extreme ultraviolet (EUV) spectrometer working in 20-500 Å wavelength range with fast time at the mid-plane[13].

3. Results and discussions

3.1 Impurity seeding from lower(carbon) and upper(tungsten) divertor

Shot #56467 ran with conditions as follows: I_p=0.5 MA, B_T=2.5 T, line integrated density n_e≈2.7×10^{19} m^{-3}. Fig.2 shows the time evolution of this L-mode discharge under the LSN divertor configuration with∇B drift towards the upper divertor and the divertor cryo-pump being activated. The heating power was 1.4 MW by low hybrid waves. Ar mixture had been injected near the lower inboard target strike point at the rate of 2.0~2.6×10^{20} e^-/s since 6.0s for 200ms. After a delay time of 100 ms, the effect of Ar actually started at about 6.1s. The heat flux, q_t, on the divertor target plate, was clearly reduced, i.e. by ~3 times, the ion saturation current I_s and electron temperature T_e, measured by divertor Langmuir probe, were decreased by 40% and 35% near the strike point, because the ionization of the seeded neutral gas had led to the rise of radiation to exhaust power in the divertor region. The plasma partially detached on lower inboard target. And a more interesting thing is that the rise of radiation, measured by AXUV, mainly distribute on upper and lower divertor region when the Ar impurity seeded from lower divertor. The main reason may be the transportation of the impurity ion along with∇B drift direction and ionization in upper divertor region. Further experiments are required to confirm this phenomenon and its mechanism.

Like Shot #56467, Shot #56649 was an L-mode discharge under the LSN configuration, and the conditions are: I_p=0.4 MA, B_T=2.5 T, line averaged density n_e≈2.0×10^{19} m^{-3}.These two discharges have similar parameters, but Ar injected from upper divertor target instead of lower divertor for 300 ms. Their results show clear difference on profile of radiation. The rise of radiation more concentrates on the core plasma region after the Ar mixture seeded from upper divertor target compared with the former. As Fig.3 shows, main reason is a great part of Ar impurity enter the plasma core region and bring a significant rise of radiation. It is considered that this result may have some association with plasma shape setting and divertor geometry type. In addition to, it is a notable challenge in tungsten wall condition that Ar injection led to an increase of the tungsten flux on upper divertor surface despite a reduction in electron temperature and power flux. It is difficult to observe tungsten sputtering by spectroscopy with EAST heavily Li-coating wall condition on tungsten divertor region. Fortunately, this result was founded at the end of daily discharges with the weakest of Li-coating. In that situation, the sputtered tungsten, observed by divertor tungsten spectroscopy, entered core plasma easily and thus resulted in the degradation of plasma confinement due to the burst of core radiation. Similar result for Ar seeding were discovered in ASDEX-Upgrade as well [14, 15]. It is deduced that the sputtering of tungsten is mainly ascribed to Ar impurity being ionized in boundary plasma and accelerated to the target due to sheath potential. However, the count of tungsten is still in commissioning because the tungsten and argon signals have an overlap in this wavelength range.

3.2 Different setting of puffing pulse

As is well-known, EAST upgraded its upper divertor into actively-cooled W/Cu PFCs in 2014[16]. To prove the capacity of heat load and find an effective way to control the heat flux on upper divertor target, impurity seeding experiments under USN divertor configuration H-mode condition carried out during 2015 campaign firstly. Injection method is the major factor with regard to the effect of impurity seeding from our and other devices' experience. Experiment results show that the pulse width, amplitude and repetition frequency of gas puffing, as well as seeding position, had a significant influence on plasma performance[17]. Long pulse and short pulse were set before seeding in USN divertor configuration H-mode plasma. In Shot#57417 and #57423(see Fig. 5), B_t was set at 2.5 T and I_p=0.4 MA, and the heating power around 4.3 MW with ICRF of 1.5MW and LHW of 2.8 MW. The Ar impurity had been seeded from upper outboard target at the rate of $2.2\sim2.7\times10^{20}$ e^-/s for 200 ms. During gas puffing, the rise of radiated power measured by AXUV was about 350 kW. So that the heat flux on divertor observed by LP was clearly reduced about 75%. However, the entire plasma energy decreased by less than 5%, and it returned to initial state very quick after gas puffing. The latter shot, as Fig.4 shown, with long pulse of Ar seeding set at the rate of $0.9\sim1.4\times10^{20}$ e^-/s for 1000ms, this H-mode plasma lost 32 kJ energy, 35% of whole plasma stored energy, ascribed to the excessive loss of radiated power, and then H- to L-mode transition was observed. The main reason is Ar impurity enters the plasma core region easily and Ar is a quite strong radiator in electron temperature T_e at 2 to 3 hundreds eV. It indicated that using a single continuous long pulse Ar seeding is possibly of great risk when feedback controlled divertor gas puffing system is still underconstructed in EAST.

3.3 Preliminary results of Ne seeding experiment

To compare with Ar seeding, Ne seeding experiment was carried out in EAST 2016 spring campaign. Moreover, this is first time we take Ne as the radiator on EAST machine after EAST upgraded its upper tungsten divertor and divertor gas puffing system. In these L-mode USN divertor configuration discharges with 2.0 MW LHW heating, and the conditions are: I_p=0.4 MA, B_t=2.3 T, line integrated density $n_e\approx2.2\times10^{19}$ m^{-3}. According to the cooling factor of Ne, a small amount of pure Ne was seeded from upper divertor outer target. After Ne seeded, the plasma electron temperature on upper divertor outer target decreased by less than 5 eV (see Fig. 6). There is a peak of Ne's cooling factor L_z in 20-40 eV[18], which is the electron temperature in the divertor region during this discharge. The experiment proved the efficiency of Ne impurity in reducing the heat load. In addition, compared with Ar seeding, as Fig.7 shows, the rise of radiation more located in the divertor region under similar parameters' condition and the same gas puff position. The experimental result on EAST shows that Ar seeding is prone to a core radiation compared to Ne seeding that Ar impurity enter core plasma more easily and its cooling factor much higher than Ne's in the plasma core region. Thus, Ne impurity will be preferred in the future radiative divertor experiment.

4. Summary

Radiative divertor experiments with Ar seeding have been carried out during recent EAST campaigns.The Ar mixture and Ne as the radiators were seeded from the divertor region under the different confinment modes and divertor. Experiments proved the high efficiency of Ar and Ne impurities in reducing heat load and particle flux. However, PFCs sputtering, especially tungsten sputtering, and core plasma contamination were observed with Ar seeding. Ar is also a strong radiator for EAST, and excessive Ar impurity will easily cause the burst of radiation and lead a great loss of stored energy in core plasma, which is unfavorable for long pulse high performance operation. Compared to Ar seeding, Ne shows advantages on distribution of radiation rise and control of core plasma contamination.

Thus, in the future, Ne will be used as the radiator preferentially. Not only Ne impurity but also other impurities such as nitrogen (without Li coating) will be tested for steady long-pulse partial detached plasma. Moreover, accroding to the result of setting different seeding pulse, modulation method of gas puffing will be tried out in future EAST campaign.

Acknowledgements

This work was supported by the National Natural Science Foundation of China No.11575242, No.11305214 and National Magnetic Confinement Fusion Science Program No. 2013GB105002.

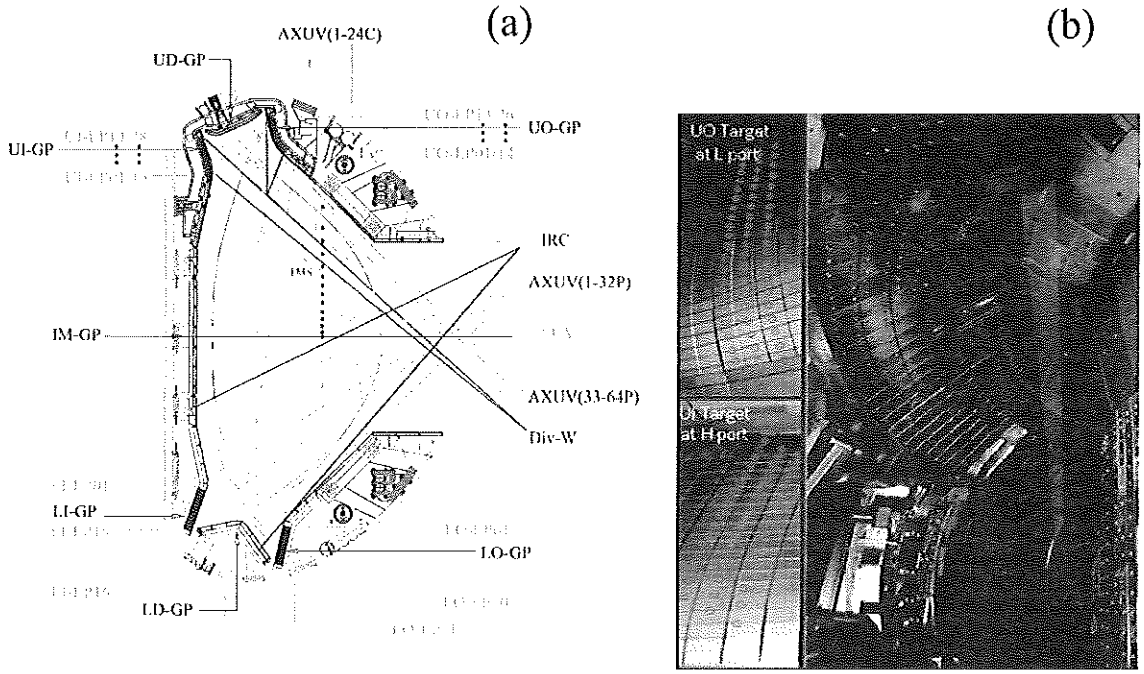


Figure 1. (a)Poloidal cross secion of EAST showing relavant diagnostics of the experiments and divertor gas puff locations. AXUV- absolute extreme ultraviolet bolometer arrays; U(L)I-upper(lower) inboard divertor; U(L)O-upper(lower) outboard divertor; U(L)D- upper (lower) divertor dome; GP-gas puff inlet; IM- inner midplane; TMS-Thomson scattering; IRC-infrared camera; EUV- extreme ultraviolet spectrometer; Div-W: divertor tungsten spectroscopy. (b)EAST first wall and observable region of divertor tungsten spectroscopy.

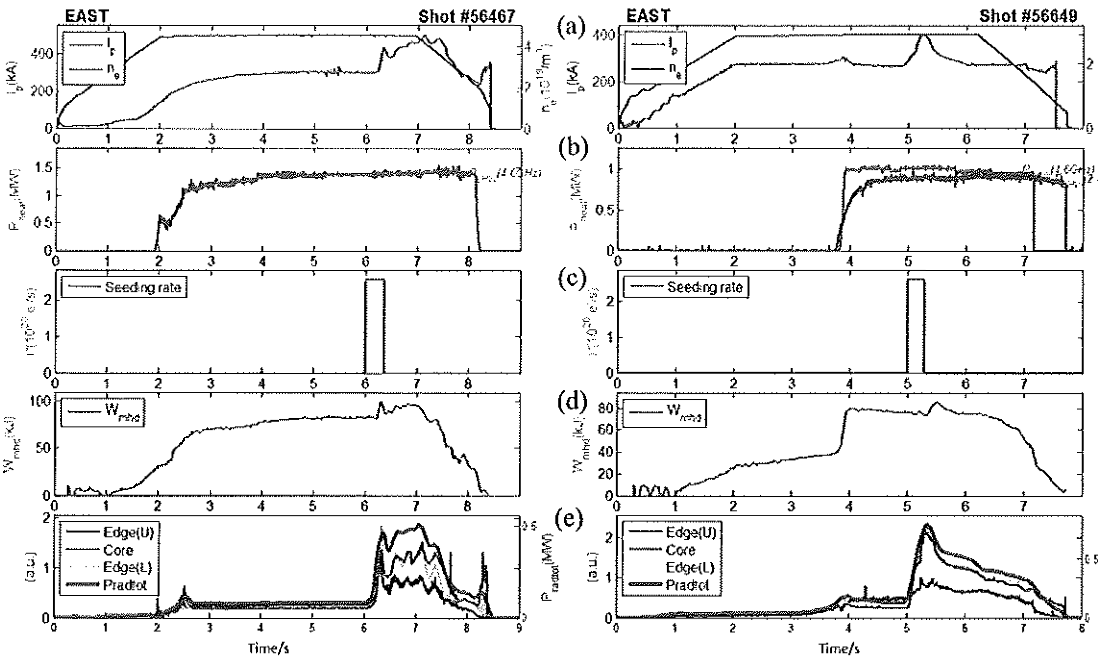


Figure 2. Time evolution of Shot#56467 and Shot#56649. (a)Line intergrated density (n_e) and plasma poloidal current (Ip). (b)Heating power: 2.45GHz LHW,4.6GHz LHW and ICRF. (c)Impurity seeding rate. (d) Stroed energy of plasma:W_{mhd} (e) Core,upper divertor,lower divertor region line intergrated radiation and total radiation power.

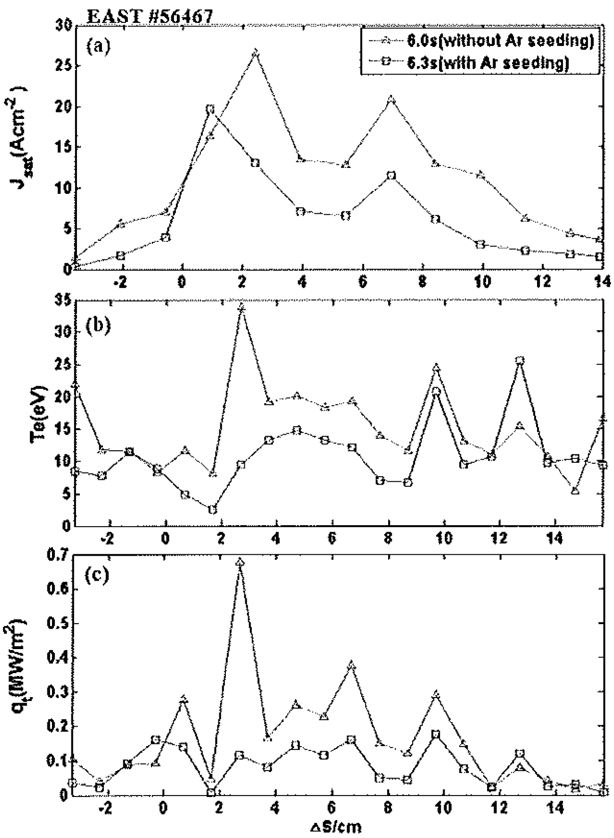
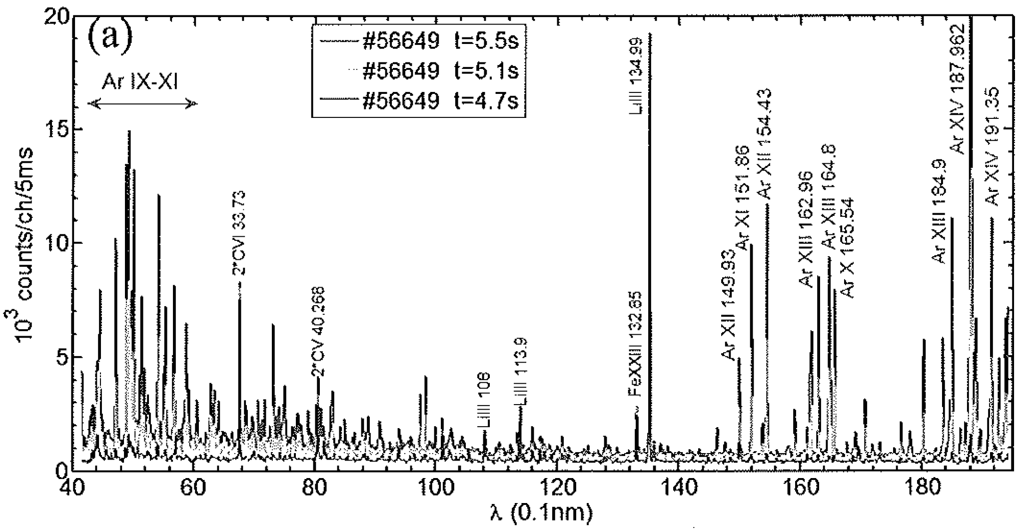


Figure 3. Shot #56467: Langmuir probe measurements on lower divertor target. (a) saturation ion current (b) electron temperature (c) vertical heat flux onto the target.



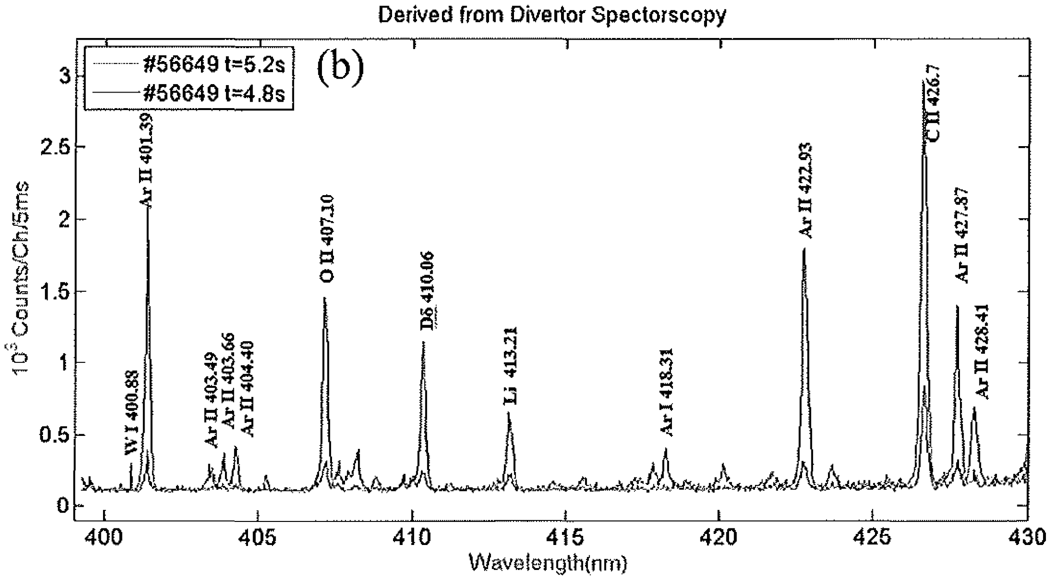


Figure 4. (a) Impurities at the mid-plane obsevered by EUV spectrometer before (4.7s), during (5.1s), and after (5.5s) Ar seeding (b) Impurities in upper divertor region obsevered by div-W spectroscopy without Ar seeding (4.8s) and with Ar seeding (5.2s).

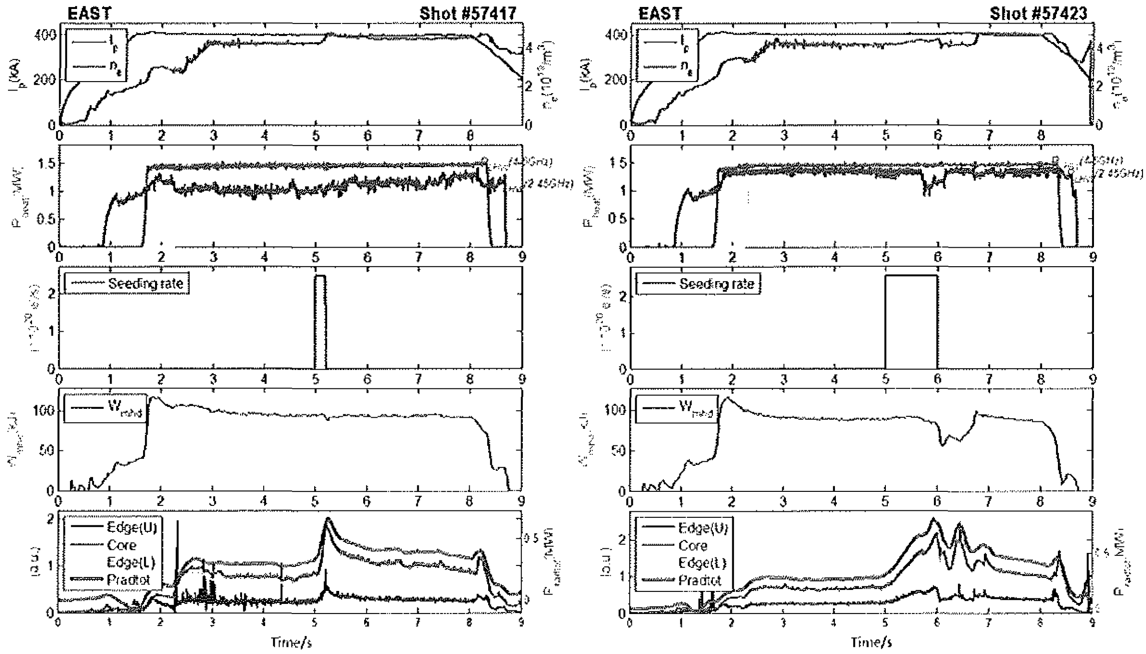


Figure 5. Time evolution of plasma parameters for Shot#57423. Same parameters as shown in Fig. 2.

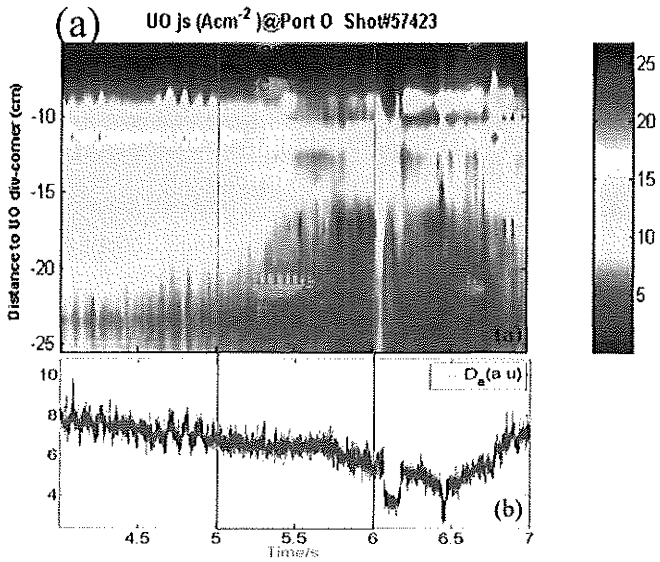


Figure 6. (a)Distribution of saturation ion current measured by Langmuir probe in upper divertor region (b)D_α signal.

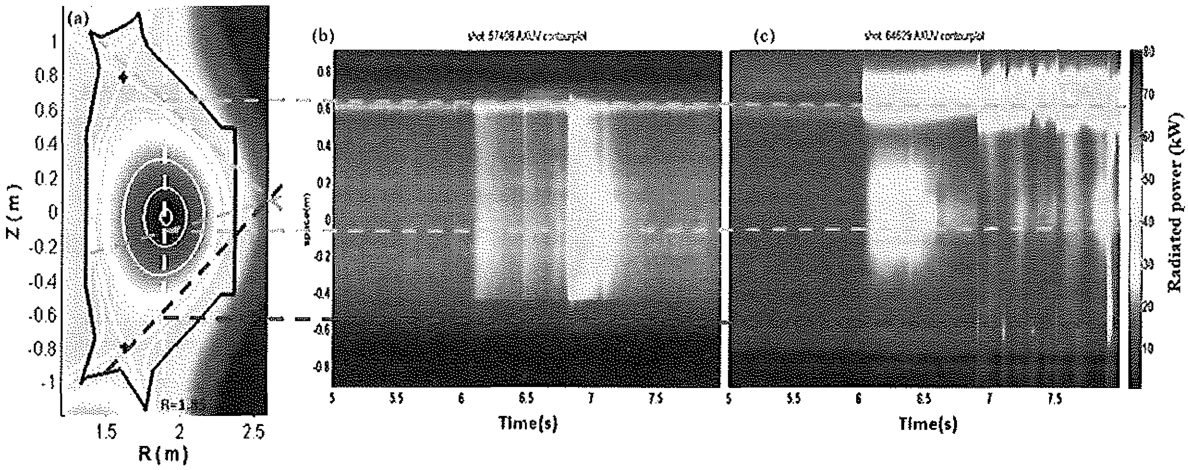


Figure 7. Radiation profile for Shot#57408(Ar seeding) and Shot#64629(Ne seeding). The dotted line in (a) represents the locations in (b) and (c).

References

[1] F. Reimold, M. Wischmeier, M. Bernert, S. Potzel, A. Kallenbach, H.W. Müller, B. Sieglin, U. Stroth, Divertor studies in nitrogen induced completely detached H-modes in full tungsten ASDEX Upgrade, Nuclear Fusion 55 (2015) 033004.

[2] A. Kallenbach, M. Bernert, M. Beurskens, L. Casali, M. Dunne, T. Eich, L. Giannone, A. Herrmann, M. Maraschek, S. Potzel, F. Reimold, V. Rohde, J. Schweinzer, E. Viezzer, M. Wischmeier, Partial detachment of high power discharges in ASDEX Upgrade, Nuclear Fusion 55 (2015) 053026.

[3] G.P. Maddison, C. Giroud, B. Alper, G. Arnoux, I. Balboa, M.N.A. Beurskens, A. Boboc, S. Brezinsek, M. Brix, M. Clever, R. Coelho, J.W. Coenen, I. Coffey, P.C. da Silva Aresta Belo, S. Devaux, P. Devynck, T. Eich, R.C. Felton, J. Flanagan, L. Frassinetti, L. Garzotti, M. Groth, S.

Jachmich, A. Jarvinen, E. Joffrin, M.A.H. Kempenaars, U. Kruezi, K.D. Lawson, M. Lehnen, M.J. Leyland, Y. Liu, P.J. Lomas, C.G. Lowry, S. Marsen, G.F. Matthews, G.K. McCormick, A.G. Meigs, A.W. Morris, R. Neu, I.M. Nunes, M. Oberkofler, F.G. Rimini, S. Saarelma, B. Sieglin, A.C.C. Sips, A. Sirinelli, M.F. Stamp, G.J. van Rooij, D.J. Ward, M. Wischmeier, J.E. Contributors, Contrasting H-mode behaviour with deuterium fuelling and nitrogen seeding in the all-carbon and metallic versions of JET, Nuclear Fusion 54 (2014).

[4] T. Nakano, J.T. Team, Comparison of Ne and Ar seeded radiative divertor plasmas in JT-60U, Journal of Nuclear Materials 463 (2015) 555-560.

[5] D.S. Wang, H.Y. Guo, Y.Z. Shang, K.F. Gan, H.Q. Wang, Y.J. Chen, S.C. Liu, L. Wang, W. Gao, L.Y. Xiang, Z.W. Wu, G.N. Luo, E. Team, Radiative Divertor Plasma Behavior in L- and H-Mode Discharges with Argon Injection in EAST, Plasma Science & Technology 15 (2013) 614-618.

[6] H.Y. Guo, J. Li, X.Z. Gong, B.N. Wan, J.S. Hu, L. Wang, H.Q. Wang, J.E. Menard, M.A. Jaworski, K.F. Gan, S.C. Liu, G.S. Xu, S.Y. Ding, L.Q. Hu, Y.F. Liang, J.B. Liu, G.N. Luo, H. Si, D.S. Wang, Z.W. Wu, L.Y. Xiang, B.J. Xiao, L. Zhang, X.L. Zou, D.L. Hillis, A. Loarte, R. Maingi, Approaches towards long-pulse divertor operations on EAST by active control of plasma-wall interactions, Nuclear Fusion 54 (2014) 013002.

[7] H.Y. Guo, J. Li, B.N. Wan, X.Z. Gong, Y.F. Liang, G.S. Xu, X.D. Zhang, S.Y. Ding, K.F. Gan, J.S. Hu, L.Q. Hu, S.C. Liu, J.P. Qian, Y.W. Sun, H.Q. Wang, L. Wang, T.Y. Xia, B.J. Xiao, L. Zeng, Y.P. Zhao, P. Denner, J.R. Ferron, A.M. Garofalo, C.T. Holcomb, A.W. Hyatt, G.L. Jackson, A. Loarte, R. Maingi, J.E. Menard, M. Rack, W.M. Solomon, X.Q. Xu, M. Van Zeeland, X.L. Zou, Recent advances in long-pulse high-confinement plasma operations in Experimental Advanced Superconducting Tokamaka), Physics of Plasmas 21 (2014) 056107.

[8] B.N. Wan, J.G. Li, H.Y. Guo, Y.F. Liang, G.S. Xu, L. Wang, X.Z. Gong, A. Garofalo, E.T. Collaborators, Advances in H-mode physics for long-pulse operation on EAST, Nuclear Fusion 55 (2015) 20.

[9] W. Wang, Upgrade of gas puffing system and preliminary results in EAST radiative divertor experiment, University of Chinese Academy of Sciences, 2015.

[10] J.C. Xu, L. Wang, G.S. Xu, e. al., Upgrade of Langmuir probe system for actively water-cooled, ITER-like tungsten mono-block divertor on the EAST superconducting tokamak, submitted to Rev.Sci.Instrum (2016).

[11] T. Ming, W. Zhang, J. Chang, J. Wang, G.S. Xu, S. Ding, N. Yan, X. Gao, H.Y. Guo, Improvement of divertor triple probe system and its measurements under full graphite wall on EAST, Fusion Engineering and Design 84 (2009) 57-63.

[12] Y.M. Duan, L.Q. Hu, S.T. Mao, P. Xu, K.Y. Chen, S.Y. Lin, G.Q. Zhong, J.Z. Zhang, L. Zhang, L. Wang, Measurement of Radiated Power Loss on EAST, Plasma Science & Technology 13 (2011) 546-549.

[13] L. Zhang, S. Morita, Z. Xu, Z. Wu, P. Zhang, C. Wu, W. Gao, T. Ohishi, M. Goto, J. Shen, Y. Chen, X. Liu, Y. Wang, C. Dong, H. Zhang, X. Huang, X. Gong, L. Hu, J. Chen, X. Zhang, B. Wan, J. Li, A fast-time-response extreme ultraviolet spectrometer for measurement of impurity line emissions in the Experimental Advanced Superconducting Tokamak, The Review of scientific instruments 86 (2015) 123509-123509.

[14] A. Kallenbach, M. Balden, R. Dux, T. Eich, C. Giroud, A. Huber, G.P. Maddison, M. Mayer, K. McCormick, R. Neu, T.W. Petrie, T. Pütterich, J. Rapp, M.L. Reinke, K. Schmid, J. Schweinzer, S. Wolfe, Plasma surface interactions in impurity seeded plasmas, Journal of Nuclear Materials 415 (2011) S19-S26.

[15] A. Kallenbach, M. Bernert, T. Eich, J.C. Fuchs, L. Giannone, A. Herrmann, J. Schweinzer, W. Treutterer, Optimized tokamak power exhaust with double radiative feedback in ASDEX Upgrade, Nuclear Fusion 52 (2012) 122003.

[16] D.M. Yao, G.N. Luo, Z.B. Zhou, L. Cao, Q. Li, W.J. Wang, L. Li, S.G. Qin, Y.L. Shi, G.H. Liu, J.G. Li, Design, R&D and commissioning of EAST tungsten divertor, Physica Scripta 2016 (2016) 014003.
[17] D.S.Wang, Study of divertor plasma physics and impurity injection behavior on EAST, University of Science and Technology of China, 2012.
[18] A. Kallenbach, M. Bernert, R. Dux, L. Casali, T. Eich, L. Giannone, A. Herrmann, R. McDermott, A. Mlynek, H.W. Müller, F. Reimold, J. Schweinzer, M. Sertoli, G. Tardini, W. Treutterer, E. Viezzer, R. Wenninger, M. Wischmeier, Impurity seeding for tokamak power exhaust: from present devices via ITER to DEMO, Plasma Physics and Controlled Fusion 55 (2013) 124041.