Reflectometry-based Plasma Position Feedback Control Demonstration at ASDEX Upgrade

J. Santos[1], L. Guimarãis[1], M. Zilker[2], W. Treutterer[2], M. Manso[1] and the ASDEX Upgrade Team[2]

[1] Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear - Laboratório Associado, Instituto Superior Técnico, Universidade Técnica de Lisboa, 1049-001, Lisboa, Portugal

[2] Max-Planck Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany

E-mail: `jsantos@ipfn.ist.utl.pt`

Abstract. In fusion experiments, real-time feedback control of the plasma position plays a vital role for machine protection and disruption avoidance. This control task is presently performed using magnetic measurements that, in future long pulse tokamak devices of the ITER class, may be affected by drifting integrators or radiation induced voltages in the magnetic pickup coils. These effects could have impact on the magnetic equilibrium reconstruction, causing potential losses of position control and, consequently, leading to premature discharge termination or plasma facing component damage. Frequency Modulated Continuous Wave (FMCW) O-mode reflectometry, a non-magnetic dependent technique used to measure the density profile, was proposed to backup or complement the standard magnetic based control in such devices. This new control scheme has just been successfully demonstrated for the first time on the ASDEX Upgrade (AUG) tokamak. The location of the plasma boundary, used in the control of the plasma column position, was tracked in real-time (RT) using dedicated algorithms and a new approach that combines the reflectometry edge profile and a scaled line integrated density measurement from interferometry. Although feasibility studies on the viability of this method had been previously conducted at AUG, the capabilities required to produce this on-line demonstration were only incorporated in the diagnostic after a recent upgrade of its data acquisition and processing hardware. The results herein presented show the first successful demonstration of the Reflectometry Plasma Position application as proposed for ITER.

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1. Introduction

FMCW O-mode reflectometry is a diagnostic technique capable of measuring the radial electron density profile independently of the magnetic reconstruction (O-mode propagation depends only on the plasma density distribution). It has been proposed to complement the magnetics in ITER for plasma position control [1], during the long steady state flat-top periods, due to its minimum access requirements and its compatibility with the harsh ITER environment. For control purposes, measurements of the edge density profile are not an identical replacement for magnetic measurements. However, when subject to some limitations, they can provide similar capabilities [2].

In present devices, position control is performed by changing the currents flowing in dedicated control coils based on the feedback of the plasma shape, namely of the plasma separatrix. Because the separatrix results exclusively from the reconstruction of the magnetic flux distribution, no direct relation with the electron density exists. Thus, a good estimation for the density just inside this flux surface is needed in order to track the gap between the separatrix and the vessel walls using a radial density profile given by reflectometry. Fortunately, for any given machine and plasma regime (Ohmic/L-mode/H–mode), there is an empirical scaling[3, 4] relating the plasma line average density, $\bar{n}_e$, and the density at the separatrix, n_{sep}. Finding the separatrix location becomes a matter of retrieving the position of the estimated density layer from the reconstructed reflectometry profile. In practice, the on-line estimation of the density at the separatrix can be accomplished using a set of *a priori* known regime characteristic scaling factors and the interferometry core line integrated density measurement. During the nearly steady state phases, the length of the chord used to calculate the averaged line density from the interferometer's integrated density measurement can safely be assumed to be fixed ($2a = 1\,\mathrm{m}$ in the AUG case) without incurring in significant errors. This position estimation procedure proved to be very robust in H-mode regimes, the main ITER reference scenario, where the separatrix lies inside the steep and narrow edge transport barrier. In these regimes, the observed discrepancies between the used on-line $\bar{n}_e$ approximation and the one calculated *a posteriori* with a magnetically inferred chord length were never higher than 7-8%. For scalings $n_{sep}/\bar{n}_e < 60\%$, the maximum error introduced in the separatrix density estimation is always below 4.8%. On AUG these errors are typically in the $0 - 0.4 \times 10^{19}\,\mathrm{m}^{-3}$ range, what corresponds to a variation of the estimated separatrix position of just few millimeters ($\ll 1\,\mathrm{cm}$ - ITER's required accuracy).

2. Demonstration background

Until the herein reported experiments, plasma position control based on O-mode reflectometry was a control technique proposed for ITER that still needed to be fully validated in a present fusion device. An early offline proof-of-principle was carried out in ASDEX Upgrade [5, 2], a particularly suited device for this purpose due to its ITER relevant geometry and plasma regimes, as well as to its unique O-mode broadband reflectometry system[6], capable of probing the plasma simultaneously at the high (HFS) and low (LFS) field sides. However, to bring this technique to an on-line operational status it was necessary to develop dedicated algorithms to reliably compute the reflectometry density profiles in RT and to test the methods used to infer the location of the plasma boundary (separatrix) from the profile measurements [7]. In fact, reflectometry has been a well-established technique used to produce detailed off-line profile measurements, for physics studies purposes. The standard data-processing techniques employed to produce these measurements are not well adapted for non-interactive real-time implementations, capable of robustly producing the density profiles required by the plasma position control application. For this reason, a new technique to provide profile measurements with these characteristics, meeting at the same time ITER's feedback control spatial and temporal resolution requirements, was developed [7]. The implemented solution associates the efficiency of time-frequency Fourier analysis to the non-linear regression capabilities of neural networks. It simultaneously addresses the problems caused by the lack of reflectometry data at the lowermost densities (in O-mode propagation it is not possible to probe the plasma for densities below $0.3 \times 10^{19}\,m^{-3}$) and the effects of plasma turbulence, that cause scattering and refraction of the probing microwaves. Given the good generalization capabilities of neural networks the implemented inversion technique is very robust, producing excellent results without requiring any on-line supervised adjustment or adaptation.

Tuning the separatrix tracking procedure became a matter of using the continuous streams of density profiles, produced using the RT technique, to find and validate the characteristic scaling for the plasma regimes of interest. In the particular case of H-modes, however, reflectometry measurements can be severely affected by the ELM activity phases. During these phases the assumptions made to validate the density scaling based approximation are momentarily violated. Thus, algorithms had to be developed [8] to automatically validate and discard reflectometry measurements in order to cope with the effects of these cyclic transitory periods. The final step before the full feedback control demonstration consisted in upgrading the AUG reflectometry diagnostic in order to equip it with the RT capabilities required for its integration with the AUG discharge control system (DCS)[9, 10]. Due to the particular characteristics of the reflectometry measurements and the complexity of the computations involved in the RT algorithms, this upgrade involved the development of a high-performance dedicated acquisition and data processing system[11], capable of satisfying the tight requirements imposed by the AUG fast control cycle. The upgraded diagnostic, commissioned during the 2011 experimental campaign, is now capable of continuously producing HFS and LFS edge density profiles and tracking the radial separatrix position in a 1 ms cycle during the full length of AUG discharges (10 s).

3. Plasma position feedback control demonstration

In ASDEX Upgrade, plasma position is controlled separately from plasma shape due to the configuration of its poloidal field coils. The inherent vertical instability of vertically elongated plasmas requires a separate fast feedback loop operating in a ≈ 1 ms control cycle [12, 13]. In this fast time scale, the position controller continuously monitors only the outer radial, R_{out}, and vertical, Z_I, coordinates (see Figure 1) of the plasma column to calculate the required corrective feedback actuation in the control coils. In order to accomplish a full feedback control demonstration, the reflectometry LFS separatrix estimations, R'_{out}, had to be produced not only satisfying the required accuracy, i.e. 1 cm, but also in a time scale 10× faster than the one required for the ITER control application (10 ms).

Figure 2 shows the automatically validated RT LFS density profiles used to produce the R_{out} estimation fed to the plasma position controller in the first full demonstration discharge (#27214). In this discharge, the radial position control was switched from magnetic to reflectometry input measurements in two time intervals: 1.5-2.8s and 3.5-5s. These intervals, delimited by the magenta lines in Figure 2 and the shaded areas in Figure 3 (dashed lines mark the L-H transition), occurred during the discharge's L-mode and ELMy H-mode phases, respectively. The scalings used were: $n_{sep}/\bar{n}_e = 0.45$ during the L-mode, and $n_{sep}/\bar{n}_e = 0.35$ during the H-mode phases. The switch between values was manually programmed to happen at $t = 3\,\mathrm{s}$, the time at which the L-H transition was expected to happen, as there is no reliable automatic regime detection mechanism in place at AUG. Figure 3 (top plot) shows that the controller was able to actuate the coils so that the outer plasma radial position (R'_{out} - red line from reflectometer, R_{out} - green line from magnetics) follows the control reference trajectory (black line) during the two different plasma regimes. It can also be seen that after switching to reflectometry based control some oscillations around the target trajectories occur. Because the corrective controller actuations are still being made on the confining magnetic fields and not directly on the observed density profiles, an extra non accounted delay is introduced in the control loop. The observed oscillations, most likely induced by the inadequate adaptation of the original position controller to the characteristics of the reflectometry measurements, are particularly visible at the transition between magnetic to reflectometry based control during the ELMy H-Mode ($t = 3.5\,\mathrm{s}$). At this time, the controller needed to react to and compensate an initial $\approx 1\,\mathrm{cm}$ discrepancy between the two input reference signals, due to a badly adjusted scaling used to obtain the separatrix density estimate. To improve the performance of this control approach, the dynamics of the density based position estimates and of the indirect physical interaction between the controllable confining magnetic field and the observable density evolution will have to be incorporated into the controller's transfer function.

A second experiment was carried out using the recipe of a reference discharge, previously performed during the same experimental session. Figure 4 (top plot) shows the time traces of both magnetic and reflectometry estimated separatrix positions (green and red, respectively) measured during the reference discharge (#27357), in which the position was controlled solely using the magnetic input. The scaling values found to better match the magnetic separatrix within the required 1 cm accuracy were similar to the ones used in discharge #27214, i. e. 0.45 and 0.35 for the L and H-mode phases, respectively. As expected, no wobbling of the magnetic position is observed as its value is used in the feedback loop to control the position of the actual magnetic confinement cage. Figure 5 shows the time traces of the second discharge (#27372) in which the position control was handed to reflectometry. Using the previously validated scalings allowed for a much better overall match between the magnetic separatrix and the reflectometry position estimates. In particular, during the initial controller's switch phase, no extreme actuations in the coils were necessary to maintain the plasma closer to the prescribed target position trajectory. In this discharge the position was continuously controlled with reflectometry (shaded time interval between $t = 1.5\,\mathrm{s}$ and $t = 5.5\,\mathrm{s}$) from the L-mode phase to almost the end of the H-mode phase, long after the plasma column radial scan performed at $t \approx 4\,\mathrm{s}$. The effectiveness of developed algorithms[8] to automatically handle the effects of the large type-I ELMs is clearly seen in the just slight increase of the R'_{out} excursion observed on the uninterrupted stream of reflectometry position estimates (produced every 1 ms) during the ELMy phases.

Taking into account that, in these first feedback control experiments, the controller settings were still adjusted for the standard magnetic control, the obtained results are a clear evidence of the reflectometry based approach robustness. Furthermore, it should be noted that the input signal to be replaced by the reflectometry estimates, R_{out}, is the absolute outermost radial location of the separatrix and, hence, intrinsically dependent on the plasma shape but not on its *de facto* vertical position, Z_I. The fact that the outer reflectometer is probing the plasma through an equatorial line of sight that is, nonetheless, fixed at a Z coordinate close but not necessarily equal to Z_I, influences the quality of the R'_{out} estimate, depending on the actual plasma column vertical position and triangularity at any given time. This limitation, however, produced no severe observable effects in these particular demonstration discharges. In fact, for elongated plasmas, such as AUG's or ITER's, the reduced vertical displacement allowed for the plasma column during the steady state and the almost flat geometry of the magnetic surfaces at the equatorial plane guaranty that this issue has a limited impact on the implemented control scheme. However, these conditions will not be met when probing the plasma along lines of sight oblique to the magnetic surfaces, the case of ITER's mid and upper plasma position reflectometers. To simulate such propagation conditions, using the AUG's equatorial reflectometers, experimental tests were performed in the past [14, 15] by significantly changing the vertical position of the plasma column ($\Delta Z \approx 14\,\mathrm{cm}$). Although the obtained results shown that reflectometry density profile measurements can survive these non optimal conditions, a more in-depth study to assess the actual measurement accuracy and possible correction schemes is presently underway.

In the future, and for strict machine protection purposes, designing a backup position controller based on monitoring gaps to fixed or selected control density layers, at the reflectometers' lines of sight, would make a more effective use of the direct position information provided by the reflectometry density profile measurements.

4. Concluding Remarks

We have successfully demonstrated that the presented alternative control technique, essential for basic machine protection on ITER, can be effectively used as a backup or complement to the standard magnetic diagnostic in ITER relevant regimes, namely in the most demanding type-I ELMy H-mode. Presently, and using the developed algorithms and dedicated hardware upgrades, the ASDEX Upgrade reflectometry diagnostic produces routinely real-time density profile and control boundary location information. The experimental data gathered during the present and future campaigns will be used to optimize the controller settings and the separatrix position estimation algorithms to improve the performance of the reflectometry based plasma position feedback control approach. A potential upgrade consists in using the second equatorial microwave reflectometer, located at the High Field Side, to simultaneously control the inner and outer plasma radius. These experiments represent an important step towards establishing a mature non-magnetic position control system. Alternative control schemes, such as the presented one, are of key importance for ITER and, in the longer run, for future fusion power plants, which will have to operate with a very limited set of robust diagnostics.

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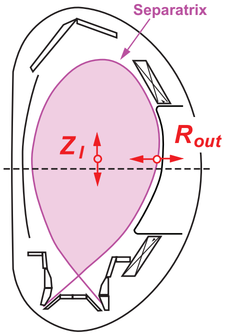

Figure 1. Fiducial points (Z_I and R_{out}) used for position feedback control in ASDEX Upgrade.

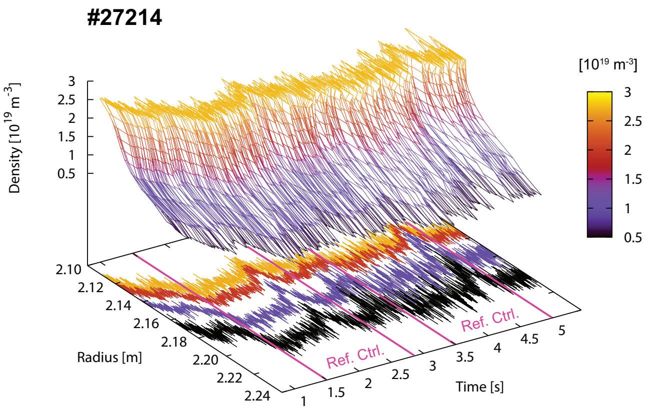

Figure 2. Validated real-time reflectometry density profiles, used for the estimation of the separatrix position (R'_{out}) fed to the position controller.

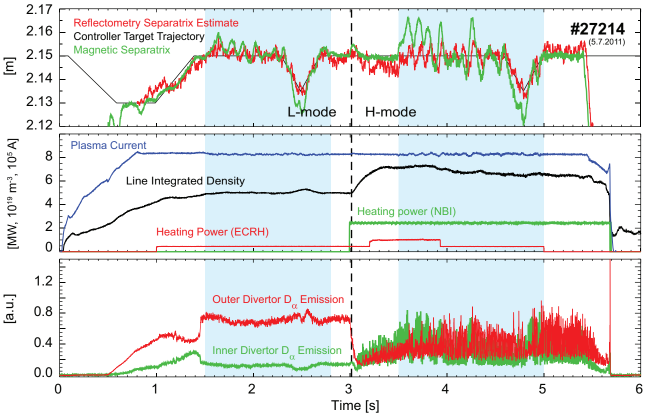

Figure 3. Time traces of the position controller target trajectory and of the input magnetic and reflectometric separatrix positions (reflectometry based control was performed during the shaded periods) - first demonstration discharge.

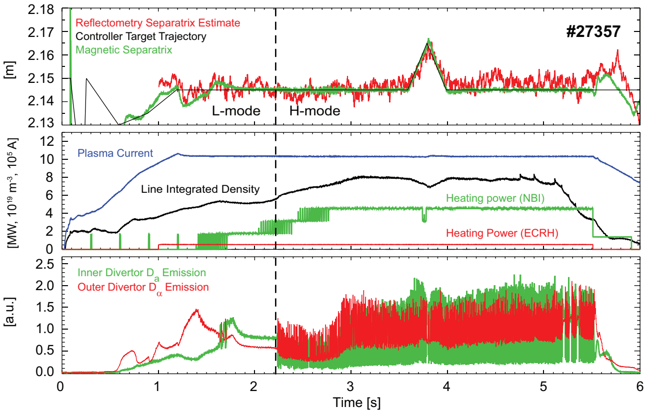

Figure 4. Time traces of the position controller target trajectory and of the magnetic and reflectometric separatrix positions (no reflectometry based control).

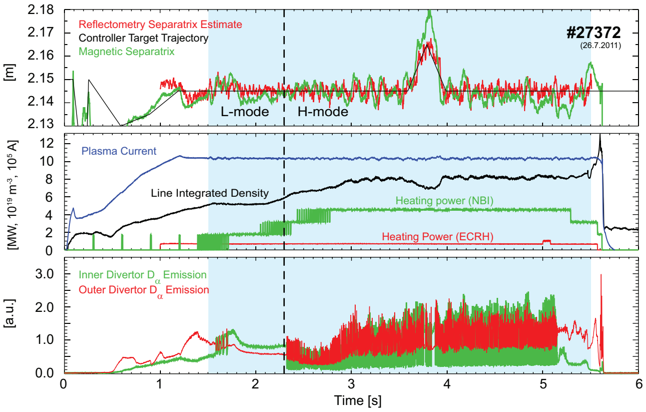

Figure 5. Time traces of the position controller target trajectory and of the magnetic and reflectometric separatrix positions (reflectometry based control was performed during the shaded period) - second demonstration discharge.

[1] N. L. Bretz, C. Kessel, E. J. Doyle, and G. Vayakis. ITER position control reflectometry - conceptual design. In Stott. P. E., Giuseppe Gorini, Paolo Prandoni, and Elio Sindoni, editors, *Diagnostics for experimental thermonuclear fusion reactors 2*, pages 129–137, New York, 1998. Plenum Press.

[2] J. Santos, S. Hacquin, and M. Manso. Frequency modulation continuous wave reflectometry measurements of plasma position in asdex upgrade ELMy H-mode regimes. *Review of Scientific Instruments*, 75(10):3855–3858, 2004.

[3] G. D. Porter, S. Davies, B. LaBombard, A. Loarte, K. McCormick, R. Monk, M. Shimada, and M. Sugihara. Analysis of separatrix plasma parameters using local and multi-machine databases. *Journal of Nuclear Materials*, 266-269(0):917–921, 1999.

[4] J. Schweinzer, W. Sandmann, G. Haas, J. Neuhauser, H. Murmann, and H. Salzmann. Comparison of scrape-off layer behaviour between DIV-I and DIV-II operations on ASDEX-Upgrade. *Journal of Nuclear Materials*, 266-269(0):934–939, 1999.

[5] J. Santos, M. Manso, P. Varela, J. Neuhauser, and the ASDEX Upgrade Team. Plasma position measurements from ordinary FMCW reflectometry on ASDEX Upgrade. *Review of Scientific Instruments*, 74(3):1489–1492, 2003.

[6] A. Silva, L. Cupido, M. Manso, F. Serra, I. Nunes, J. Santos, P. Varela, S. Vergamota, L. Meneses, V. Grossman, F. Silva, C. Loureiro, F. Nunes, B. Kurzan, and W. Suttrop. Microwave reflectometry diagnostic for density profile and fluctuation measurements on ASDEX Upgrade. *Review of Scientific Instruments*, 70(1):1072–1075, 1999.

[7] J. Santos. *Reflectometry measurements for plasma position control purposes.* PhD thesis, Dep. Electrical Engineering - Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal, May 2008.

[8] J. Santos, L. Guimarais, M. Manso, and the ASDEX Upgrade Team. Real-time reflectometry measurement validation in H-mode regimes for plasma position control. *Review of Scientific Instruments*, 81(10):10D926, 2010.

[9] M. Reich, K. Behler, R. Drube, L. Giannone, A. Kallenbach, A. Mlynek, J. Stober, W. Treutterer, and the ASDEX Upgrade Team. Real-time diagnostics and their applications at ASDEX upgrade. *Fusion Science and Technology*, 58(3):727–732, November 2010.

[10] W. Treutterer, G. Neu, G. Raupp, T. Zehetbauer, D. Zasche, K. Lueddecke, and R. Cole. Real-time signal communication between diagnostic and control in ASDEX Upgrade. *Fusion Engineering and Design*, 85(3-4):466–469, 2010.

[11] J. Santos, M. Zilker, L. Guimarais, W. Treutterer, C. Amador, M. Manso, and the ASDEX Upgrade Team. COTS-based high-data-throughput acquisition system for a real-time reflectometry diagnostic. *IEEE Transactions on Nuclear Science*, 58(4):1751–1758, August 2011.

[12] W. Treutterer, J. Gernhardt, O. Gruber, P. McCarthy, G. Raupp, U. Seidel, and the ASDEX Upgrade Team. Plasma shape control design in ASDEX Upgrade. In *Proceedings of the 19th Symposium on Fusion Technology*, volume 1, pages 933–936, Lisbon, 1997.

[13] W. Treutterer, G. Neu, G. Raupp, D. Zasche, and T. Zehetbauer. ASDEX Upgrade's new plasma control scheme. *Fusion Engineering and Design*, 81(15-17):1927–1931, 2006.

[14] A. Silva, M. E. Manso, L. Cupido, M. Albrecht, F. Serra, P. Varela, J. Santos, S. Vergamota, F. Eusebio, J. Fernandes, T. Grossmann, A. Kallenbach, B. Kurzan, C. Loureiro, L. Meneses, I. Nunes, F. Silva, and W. Suttrop ASDEX Upgrade Team. Ultrafast broadband frequency modulation of a continuous wave reflectometry system to measure density profiles on asdex upgrade. *Review of Scientific Instruments*, 67(12):4138–4145, 1996.

[15] T Grossmann, I Nunes, F Serra, M.E Manso, and A Silva. Sensitivity of fast swept frequency modulation reflectometry to changes in magnetic configuration in asdex upgrade. *Fusion Engineering and Design*, 34-35(0):425 – 428, 1997.