Metal impurity fluxes and plasma-surface interactions in EXTRAP T2R

H Bergsåker¹, S Menmuir², E Rachlew², P R Brunsell¹, L Frassinetti¹ and J R Drake¹

¹ Div. of Fusion Plasma Physics (Association EURATOM-VR), Alfvén Laboratory, School of Electrical Engineering, Royal Institute of Technology KTH, SE-10044 Stockholm, Sweden.

² Department of Physics, School of Engineering Sciences, Royal Institute of Technology KTH, SE-10044 Stockholm, Sweden.

E-mail: henric.bergsaker@alfvenlab.kth.se

Abstract. The EXTRAP T2R is a large aspect ratio Reversed Field Pinch device. The main focus of interest for the experiments is the active feedback control of resistive wall modes [1]. With feedback it has been possible to prolong plasma discharges in T2R from about 20 ms to nearly 100 ms. In a series of experiments in T2R, in H- and D- plasmas with and without feedback, quantitative spectroscopy and passive collector probes have been used to study the flux of metal impurities. Time resolved spectroscopic measurements of Cr and Mo lines showed large metal release towards discharge termination without feedback. Discharge integrated fluxes of Cr, Fe, Ni and Mo were also measured with collector probes at wall position. Reasonable quantitative agreement was found between the spectroscopic and collector probe measurements. The roles of sputtering, thermal evaporation and arcing in impurity production are evaluated based on the composition of the measured impurity flux.

1. Introduction
The main focus of investigations at present in the EXRAP T2R reversed field pinch (RFP) is on active feedback stabilization of resistive wall modes [1]. It has been found that without feedback control the plasma resistivity starts to increase after 10-15 ms and the discharge terminates early due to lack of confinement. The increasing resistivity is accompanied by increasing amplitudes of resistive wall modes (n > -12, m = 1), the gradual slowing down of rotating tearing modes (n = -13, n = -12) and the resulting build up of a non-axisymmetric radial magnetic field at the wall. With feedback the mode amplitudes remain constant, the rotating modes keep rotating and the discharges are prolonged by a factor 2-5 [1].

The termination of discharges without feedback is clearly associated with enhanced plasma-surface interaction. It is both interesting and important from the point of view of the risks to the vacuum vessel to try and understand the nature of this plasma-surface interaction. To this end a series of experiments has been carried out where the metal impurity fluxes in discharges with and without feedback control were measured both by quantitative visible spectroscopy and using passive collector probes and surface analysis. The spectroscopic measurements provided good time resolution, while the collector
method served to cross check the quantification and gave complementary information on the composition.

2. Experimental
The EXTRAP T2R device [2] has a major radius $R = 1.24$ m and a plasma minor radius $a = 0.183$ m. The magnetic field penetration time of the conducting shell is $\tau_{\text{sh}} = 6.3$ ms. The plasma minor radius is defined by poloidal arrays of mushroom-shaped Molybdenum limiters, covering about 8% of the total inner wall area. Between the limiter sections the wall consists of 316L stainless steel bellows with the inner convolution surface at minor radius $r_w = 0.187$ m. Figure 1 shows the disposition of the limiters, the diagnostic ports and the wall. The radial density decay length at the edge is typically 8-10 mm.

Spectroscopic measurements of neutral metallic impurity lines were made using an absolutely calibrated monochromator (focal length 0.25 m). The light emitted from the plasma was collected with time resolution along a vertical line of sight through the plasma core. To simplify the comparison with collector probes the intensities of Cr I and Mo I were also integrated from 2 ms into the discharge until the end and normalized to the discharge duration to give average photon flux. The particle flux density was calculated [3] assuming the electron temperature $kT_e = 5$ eV and density $n_e = 10^{18}$ m$^{-3}$ in the region of primary emission (consistently with earlier Langmuir probe measurements).

Collector probe measurements were carried out in the same way as in the earlier EXTRAP T1 experiment [4]. Passive graphite probes were placed with the surface level and parallel with the wall in an outboard horizontal port and exposed to one or a number of complete discharges. Following exposure the probes were extracted and investigated with ion beam analysis methods at the Ångström laboratory, Uppsala University. The composition of the deposited metals was measured with Rutherford backscattering spectrometry (RBS) using 3.5 MeV $^4$He$^+$ ions and the areal density of deuterium in the case of exposure in D- plasma was measured using the $^3$H($^3$He,p)$^4$He nuclear reaction with 2 MeV $^3$He$^+$. A series of discharges with and without feedback and with $^1$H+ and $^2$H+ as majority plasma ion was studied. The particle confinement time is known to be of order $\tau_p \approx 0.3$ ms [1].

3. Results
Figure 2 compares discharges in $^1$H with and without feedback. The discharge without feedback is terminated early and the termination is preceded by increased emission from Mo and Cr. Figure 3 shows the discharge averaged fluxes of Cr and Mo throughout the series of discharges, derived from spectroscopy. Figure 4 shows an example of an RBS spectrum, with Cr, Fe, Ni and Mo collected on a graphite probe which was exposed to 8 discharges in $^1$H plasma with feedback. A linear fit is made assuming the natural isotopic composition of each element and with a linear background fit derived from measurement before exposure. The absolute accuracy for Fe and Mo should be about 5%, while for Cr and Ni it is obviously worse due to the smaller amounts. Table 1 shows the average deposition rates on five different probes, exposed in discharges in $^1$H and D, with and without feedback. The spectroscopic and probe data are in reasonable agreement, in particular in that the integrated flux of both Cr and Mo was higher without feedback than with feedback. The collector probe data also show larger fluxes for D- discharges than for $^1$H-discharges, which does not show up in spectroscopy.
**Figure 2.** Examples of emissions in discharges in H- plasmas, with and without feedback. The top panels show the plasma current. Discharges without feedback terminate prematurely and the termination is preceded by enhanced fluxes of Mo and Cr into the plasma.

**Figure 3.** Discharge averaged metal fluxes from spectroscopy. Squares: Cr. Triangles: Mo. Filled symbols: \(^1\)H plasma, Open symbols: D-plasma

**Figure 4.** Example of RBS spectrum from graphite collector probe. A linear fit is made, assuming natural isotope compositions.

At the probe surfaces which were exposed to D discharges \(5-6 \times 10^{15} \text{ D/cm}^2\) was trapped in the 153 and 489 ms long exposures and about \(10^{16} \text{ D/cm}^2\) in the 909 ms exposure. Converted to trapping rates, these numbers are about two orders of magnitudes lower than the total hydrogen flux density to the wall corresponding to typical particle confinement times measured earlier in T2R [1].
Table 1. Average deposition rates on probes at wall position, from RBS.

| sample | Cr $E_{15}/cm^2/s$ | Fe $E_{15}/cm^2/s$ | Ni $E_{15}/cm^2/s$ | Mo $E_{15}/cm^2/s$ | Exposure ms | ion feedback |
|--------|-------------------|-------------------|-------------------|-------------------|-------------|--------------|
| 10     | 0.87              | 2.5               | 0.33              | 0.54              | 543         | H            | on           |
| 11     | 1.1               | 3.8               | 0.49              | 0.76              | 148         | H            | off          |
| 17     | 1.8               | 4.6               | 1.2               | 0.80              | 489         | D            | on           |
| 18     | 5.1               | 9.2               | 3.4               | 1.6               | 153         | D            | off          |
| 20     | 2.1               | 4.9               | 0.93              | 0.91              | 909         | D            | on           |

4. Discussion and conclusions

For the comparison between spectroscopy and probes we assume toroidally and poloidally uniform fluxes. The agreement is reasonable. The composition of deposited metals does not change a lot, approximately $Cr:Fe:Ni = 0.35:1:0.15$, while for SS316L $Cr:Fe:Ni = 0.25:1:0.18$. The ratio of the collected areal densities of Mo and Fe remains approximately 20%, 2-3 times larger than the ratio of the wall areas covered by Mo and stainless steel.

Plausible mechanisms for release of metallic impurities are physical sputtering by the majority ions and by impurities, thermal evaporation and unipolar arcs. For sputtering by the majority ion, since the sputtering yield is at least twice larger for $D^+$ compared to $^1H^+$ [5], a significant difference between the isotopes should occur. A difference was observed in the collector probe data but not in spectroscopy. The ion flux is not likely to be much larger to the limiter surfaces than to the stainless steel wall, in view of the large gyro radii (about 5 mm for 10 eV $^1H^+$ and larger still for $D^+$ or impurity ions) and large density decay length. Considering the high Mo fraction it is therefore hard to believe that sputtering can be a major contributor to the impurity release, since the sputtering yield for Mo is at least an order of magnitude down compared to that of stainless steel, at energies below several hundred eV [5]. In the similar measurements in a much smaller RFP experiment [4] the trapping of deuterium increased linearly with exposure time for low fluence and reached saturation at several times $10^{16} D/cm^2$. It was concluded that the ion flux to the wall contained a significant population with energies corresponding to a Maxwellian distribution with ion temperature $kT_i \approx 100$ eV. In the present case the data indicate both low trapping rates and saturation corresponding to energies below 100 eV. From the estimated $\tau_p$ the hydrogen flux density is about two orders of magnitude larger than the measured metal redeposition flux density, while the sputtering yield of H and D incident on SS or Mo is less than 1% for energies below 100 eV. Impurity sputtering could be more important than sputtering by the majority ions, however the high Mo fraction suggest that impurity sputtering as well plays a minor role. Superthermal electrons at the edge in RFP:s carry large heat fluxes to small areas at the wall or limiters. This phenomenon is the most dangerous one to the vessel wall, as it could cause melting and even burn through the stainless steel bellow. If thermal evaporation occurs, then from vapour pressure considerations one may expect some enhancement in the Cr evaporation flux and reduction of Ni, compared to the 316L composition. From the data, such an effect could only be marginal. Again, the high and stable fraction of Molybdenum indicates that thermal evaporation is hardly a major effect either. The heat flux could be more localised to the limiters than the ion flux, but the vapour pressure of Mo is many orders of magnitude lower than that of stainless steel. Arc tracks are observed on the limiter surfaces and arcing could well be an important contributor.

References

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