LRP 401/90 April 1990

CENTRAL MASS FEEDBACK CONTROL USING THE DISCRETE ALFVEN WAVE SPECTRUM

Th. Dudok de Wit, J.B. Lister, B.P. Duval, B. Joye &
Ph. Marmillod

CENTRAL MASS FEEDBACK CONTROL USING THE DISCRETE ALFVEN WAVE SPECTRUM

Th. Dudok de Wit, J.B. Lister, B.P. Duval, B. Joye, Ph. Marmillod

Centre de Recherches en Physique des Plasmas
Association Euratom-Confédération Suisse
EPFL, 1015 Lausanne, Switzerland

ABSTRACT

The dispersion relation of the shear Alfvén wave depends on several internal plasma parameters, including the central effective mass. By frequency tracking a Discrete Alfvén Wave during the plasma current flat-top, we obtained a real-time estimate of the central effective mass. Using the measured mass, we have been able to feedback control both the effective mass and the electron density of the plasma, using separately controllable hydrogen and deuterium filling valves.

1. INTRODUCTION

The excitation of Alfvén Waves on the TCA tokamak has been documented both experimentally and theoretically [1]. Previous studies of these waves have been reported for possible current profile [2-4] and central effective mass [2] measurements. In this paper, we present the use of Discrete Alfvén Waves (DAW) both to measure and to control the effective mass of the plasma core.

For different species of ions with mass A_k and relative concentration $\eta_k = n_i/n_e$, the effective mass can be defined as the average number of nucleons per free electron

$$A_{eff} = \sum_{species} \eta_k A_k \tag{1.1}$$

This gives a value of A_{eff} of 1 for hydrogen only, 2 for deuterium, 3 for tritium and close to 2 for fully stripped impurities. A real-time measurement of A_{eff} would thereby provide a measurement of the ratio of the hydrogenic species (for example the D:T mixture ratio) which is not currently available directly.

The outline of this paper is as follows : We firstly give a description of the accessibility of the effective mass from the Alfvén wave dispersion relation. Secondly we describe the diagnostic itself and the control circuit, followed by the calibration of the diagnostic. Finally, the results of the feedback control are presented.

2. THEORETICAL BACKGROUND

In a large aspect ratio approximation, the shear Alfvén wave resonance condition is given by

$$\omega^2(r) = \frac{B_\phi^2}{\mu_o \rho(r)} \frac{\left(n + \frac{m}{q(r)}\right)^2}{R_o^2} \left(1 - \frac{\omega^2(r)}{\omega_{ci}^2}\right) \tag{2.1}$$

in which (n,m) are the toroidal and poloidal mode numbers, and $\rho(r) = n_e(r)\ A_{eff}(r)\ m_p$.

Discrete Alfvén waves occur at frequencies which are just below the thresholds of their corresponding shear Alfvén wave continua. For the low poloidal mode numbers considered in this experiment, the minima of the continua occur at the plasma centre or close to it. Therefore, the resonance frequency of the DAW is determined by the local properties of the plasma in the vicinity of r=0

$$\omega_{DAW} \lesssim \min \omega(r) \lesssim \omega(r=0) \tag{2.2}$$

Since the frequencies used are well below the ion-cyclotron frequency, we can express the effective mass as a simple function of the DAW frequency and the central electron density, by setting r to 0 in Eq. (2.1)

$$A_{eff}(0) = \frac{\kappa_{nm}}{n_{eo}\, f_{DAW}^2} \tag{2.3}$$

where the calibration factor κ_{nm} is given by

$$\kappa_{nm} = \frac{B_\phi^2}{4\pi^2 \mu_o m_p R_o^2}\left(n + \frac{m}{q_o}\right)^2 \tag{2.4}$$

Expression (2.3) agrees with results from a 1-D cold plasma simulation code [2], and confirms that the measured mass is heavily weighted by the centre of the plasma. However, this approximation could be affected by several parameters which do not appear here explicitly. These are the plasma current and its profile, the peakedness of the electron density profile and the position of the magnetic axis [2]. In order to minimise these perturbations, the experiments described were performed in quasi-steady state plasmas, with a constant plasma current and slowly evolving electron density. Under these conditions, the error on A_{eff} due to a current profile change or a magnetic axis drift, as simulated in [2], is smaller than 2%. The effect of density profile changes can be more important. If we consider a parabolic density profile

$$n_e = n_{eo}\left(1 - \frac{r^2}{a^2}\right)^{\alpha_n} \tag{2.5}$$

a 28% change in α_n typically leads to a 10% shift in A_{eff}. This error is linear with α_n ; therefore a profile correction could easily be added to the mass measurement hardware, provided the density profile is available in real time. In the experiments described in this paper, no density profile correction at all was used, since the central density in Eq. (2.3) was obtained from a line-integrated value. In such a case a much smaller profile dependence was obtained, leading to a maximum error of 2% in the mass.

3. EXPERIMENTAL SETUP

The experiments were carried out in the TCA tokamak [5] (R, a = 0.61 m, 0.18 m., $I_p \leq 170$ kA, $B_\phi \leq 1.51$ T). The Alfvén waves are launched by a small double-bar antenna positioned on the outer equatorial midplane. A rotating flange allows it to be tilted with respect to the magnetic field lines, Fig. 1. The antenna is fed by a 100 W amplifier which provides an oscillating current up to 15 A via a wideband matching circuit with a useful range of 1-6 MHz.

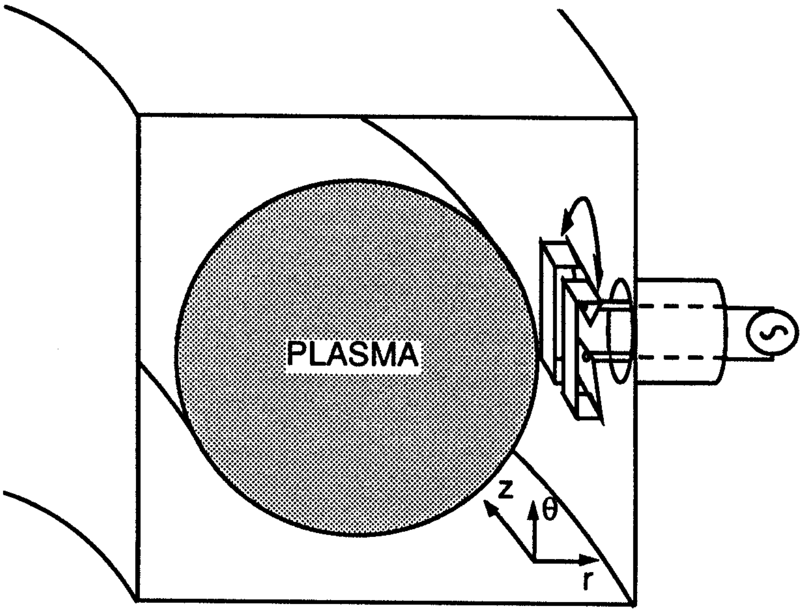

Fig. 1 *Perspective view of the antenna*

The response of the plasma to the excitation is detected by an RF magnetic pickup coil inside a ceramic finger just outside the limiter radius, which detects the toroidal RF wavefield component b_φ. The phase and amplitude of this signal are measured with reference to the antenna current, Fig. 2. Each DAW is characterised by a peak in the amplitude and a 180° phase rotation when crossing through the resonance which has a Q of about 50. The resulting phase shift allows the DAW to be tracked in frequency with a phase-locked loop. In practice, the generator frequency is adjusted to maintain either the sine or the cosine of the relative phase at zero. Earlier results [2] had proven this method to be sufficiently accurate to track a resonance with a bandwidth of up to 10 kHz.

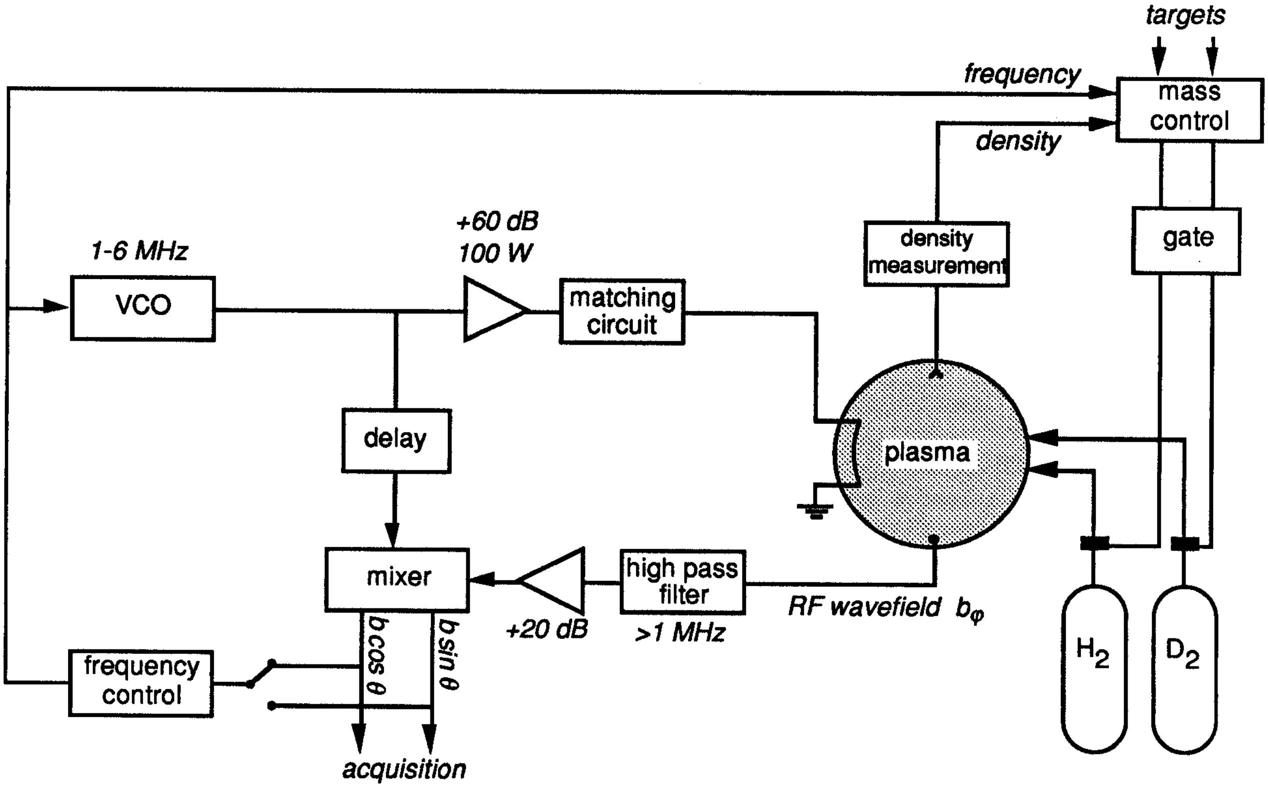

Fig. 2 *Heterodyne detection and control circuits.*

Due to its small poloidal and toroidal extent, the antenna excites a rich mixture of modes. However, since low mode numbers with small negative m are preferentially excited [1], most of the DAW resonances observed are readily identified. Once the DAW frequency and the mode numbers (n,m) are known, the inverse of the effective mass is computed in real-time using two analog multipliers and Eq. (2.3). For these real-time calculations, the central electron density is taken to be the line-averaged density multiplied by a constant. This could cause an error during strong gas puffing, if the density profile temporarily departs from its stationary shape.

All experiments described in this paper were run during the 150 ms plasma current flat-top with $I_p = 130$ kA, $q_a = 3.1$, $\bar{n}_e = 2 - 9{\cdot}10^{19}$ m^{-3}.

4. CALIBRATION

Several DAW's with different mode numbers can be detected by frequency scanning the Alfvén spectrum over a wide range. Each DAW provides an independent measurement of the effective mass. In a first experiment we repetitively scanned through several different DAW's in order to measure the effective mass over a broad density range for different hydrogen/deuterium mixtures. The deduced mass was independent of the mode numbers used, confirming the analysis and the mode number identification. In further experiments we used the two modes that were most strongly excited by the antenna, (n,m) = (–1,–1) and (–2,–1). The A_{eff} measured using these two DAW's are compared in Fig. 3, showing the excellent agreement.

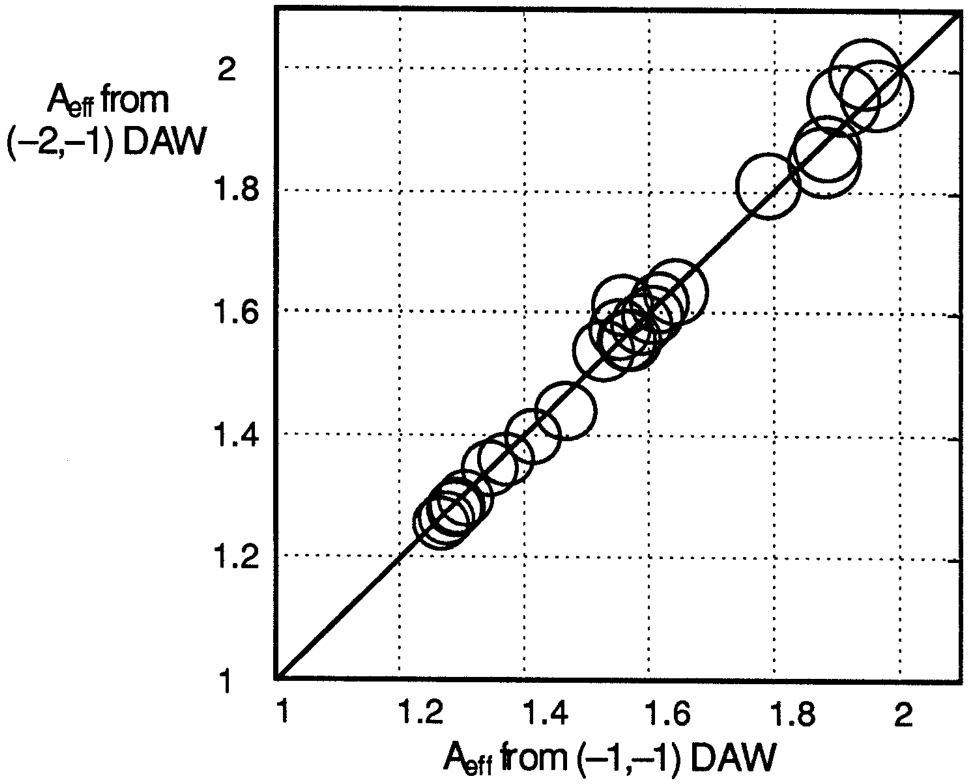

Fig. 3 Comparison of the effective mass as measured simultaneously from the (–2,–1) and the (–1,–1) DAW's, for different deuterium/hydrogen mixtures.

The mass measurement was calibrated in a deuterium plasma operated in a deuterium conditioned Tokamak vessel. In these conditions the effective mass is the least sensitive to impurity concentrations, and thus very close to 2. For each DAW, the experimental calibration coefficients κ_{nm} were obtained in this way, assuming A_{eff} to be equal to 2. These coefficients were also in reasonable agreement with the theoretical values obtained from Eq. (2.4) (units are [$MHz^2\ 10^{19} m^{-3}$]) :

theory	experiment
$\kappa_{(-1,-1)} = 31.7 \pm 1.6$	$\kappa_{(-1,-1)} = 33.5 \pm 1.1$
$\kappa_{(-2,-1)} = 70.0 \pm 2.7$	$\kappa_{(-2,-1)} = 78.4 \pm 2.4$

The experimental error of 3% is obtained from the statistical spread of the coefficients for a density range of $2\text{–}7 \cdot 10^{19}\ m^{-3}$. These systematic measurements of the effective mass in pure deuterium plasmas showed no dependence on the electron density, Fig. 4.

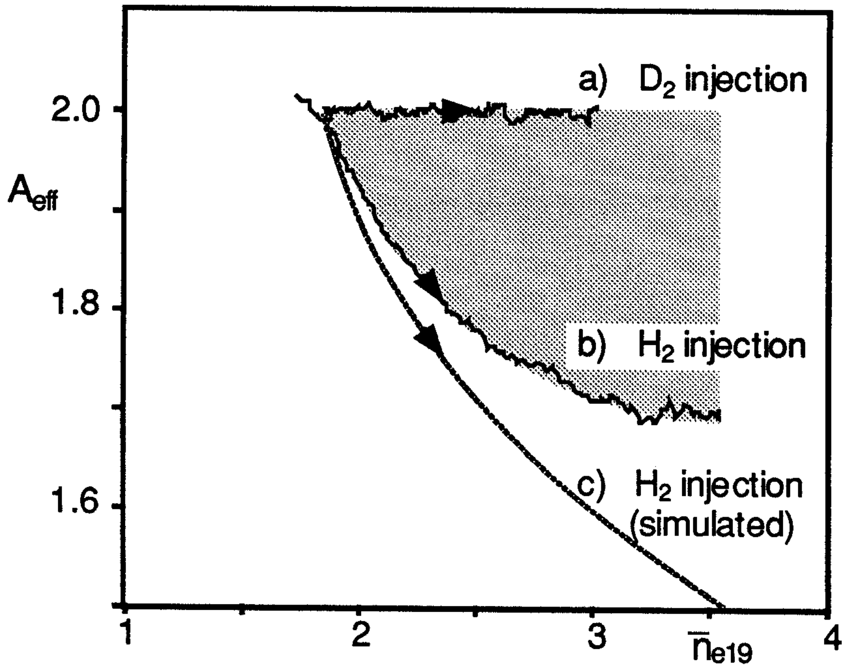

Fig. 4 *Experimental evolution of the effective mass in a deuterium filled plasma with : a) A deuterium gas puff, hydrogen valve closed (#36480); b) A hydrogen gas puff, deuterium valve closed (#36497); c) Simulated mass for a hydrogen gas puff, deuterium valve closed, assuming no recycling at the edge.*

An A_{eff} calibration in hydrogen is not as straightforward as in deuterium since the presence of impurities and residual deuterium increase the effective mass above 1. In order to find the lower A_{eff} limit, a series of discharges was made with hydrogen filling gas. The TCA tokamak vessel had previously been reconditioned by the deposition of a boron carbide layer which led to a significantly reduced impurity concentration. Glow discharge cleaning in helium or hydrogen was used to further condition the Tokamak vessel. In these conditions, the lower limit $A_{eff} = 1.06 \pm 0.04$ was measured in discharges which displayed a negligible level of D_β emission.

These experiments confirm the validity of the mass measurement as obtained from the Discrete Alfvén Wave spectrum. The diagnostic can therefore be used to monitor the hydrogen isotope concentrations which are not accessible from Z_{eff}.

5. MASS CONTROL

The real-time effective mass measurement may now be used to control the deuterium/hydrogen mixture in a Tokamak. A 2-input, 2-output feedback loop (Fig. 5) compares the analog signals $1/A_{eff}$ and $\bar{n}_e$ with two reference values pre-programmed by the operator. The resulting errors ε are coupled and the outputs act on fast hydrogen and deuterium gas valves.

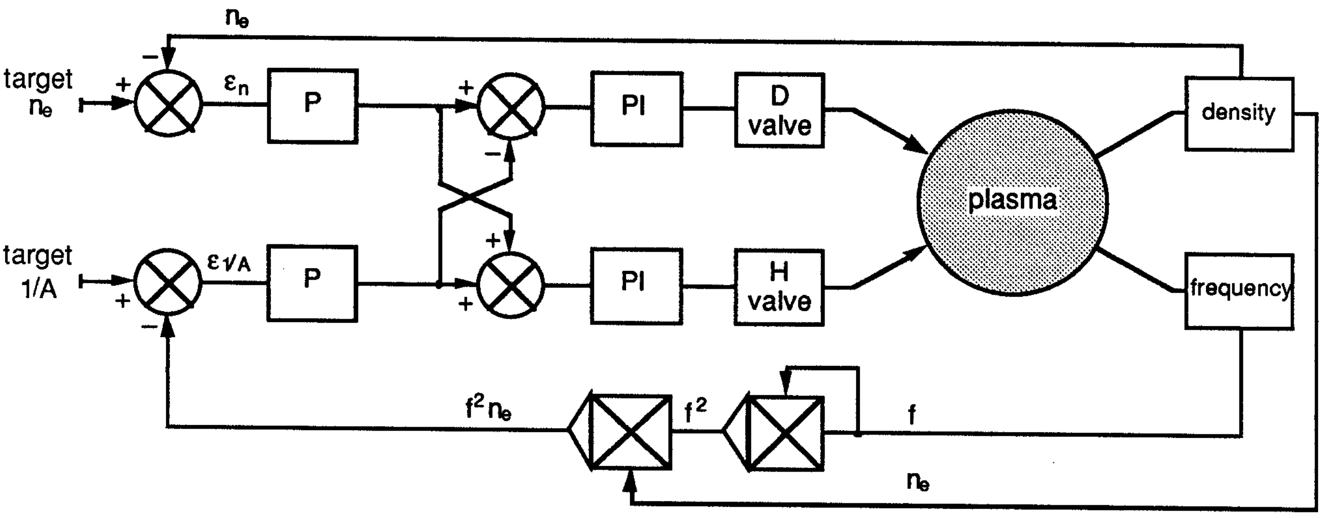

Fig. 5 *Layout of the mass and density control circuit.*

The phase-locked loop frequency control was stable and did not require further adjustment once it has been set for a particular DAW. The mass and density control was more delicate since it had two constraints :

1) For given initial density and mass values, only a limited range of (mass, density) values can be reached during the short pulse on TCA. The accessible trajectories in mass-density space are governed by the mass and density conservation laws and by the particle recycling rates at the plasma edge. For example, it is not possible to change A_{eff} significantly without affecting the density due to the long effective particle confinement time.

   The range of A_{eff} accessible from given initial conditions was measured and is shown by the shaded area in Fig. 4. This area is delimited by the trajectories corresponding to the two extreme cases : a) deuterium injection, b) hydrogen injection. Trajectory c) is calculated for a density increase which is due to hydrogen only. The discrepancy between b) and c) is caused by the high deuterium recycling rate at the plasma edge, as observed from D_β emission.

   We therefore limited ourselves to deuterium plasmas in which hydrogen was added; reasonable target ranges were $2 < \bar{n}_e < 7 \cdot 10^{19}$ m^{-3} and $1.3 < A_{eff} \leq 2$.

2) Very strong gas puffs can not only affect the accuracy of the mass measurement but may also cause major disruptions. This constraint on the puffing rate sets a lower limit to the time required to reach the target values, which in our case was between 15 and 30 ms.

Given these restrictions, we set up accessible target values for both density and effective mass. The frequency tracking circuit is locked on a chosen DAW, which can either have (n,m)=(–2,–1), Fig. 6a), or (n,m)=(–1,–1), Fig. 6b). In both cases, the mass is measured to be A_{eff}=2.0. When the mass-control is activated, either the hydrogen valve or both the hydrogen and the deuterium valves open, depending on the target mass and density. Due to the non-linear behaviour of the gas valves, a minimum voltage must be applied before gas flows into the tokamak. After that, approximately 20 ms are required to reach the target values. Figure 6 also shows the evolution of the tracked DAW frequency as both the density and the effective mass are controlled.

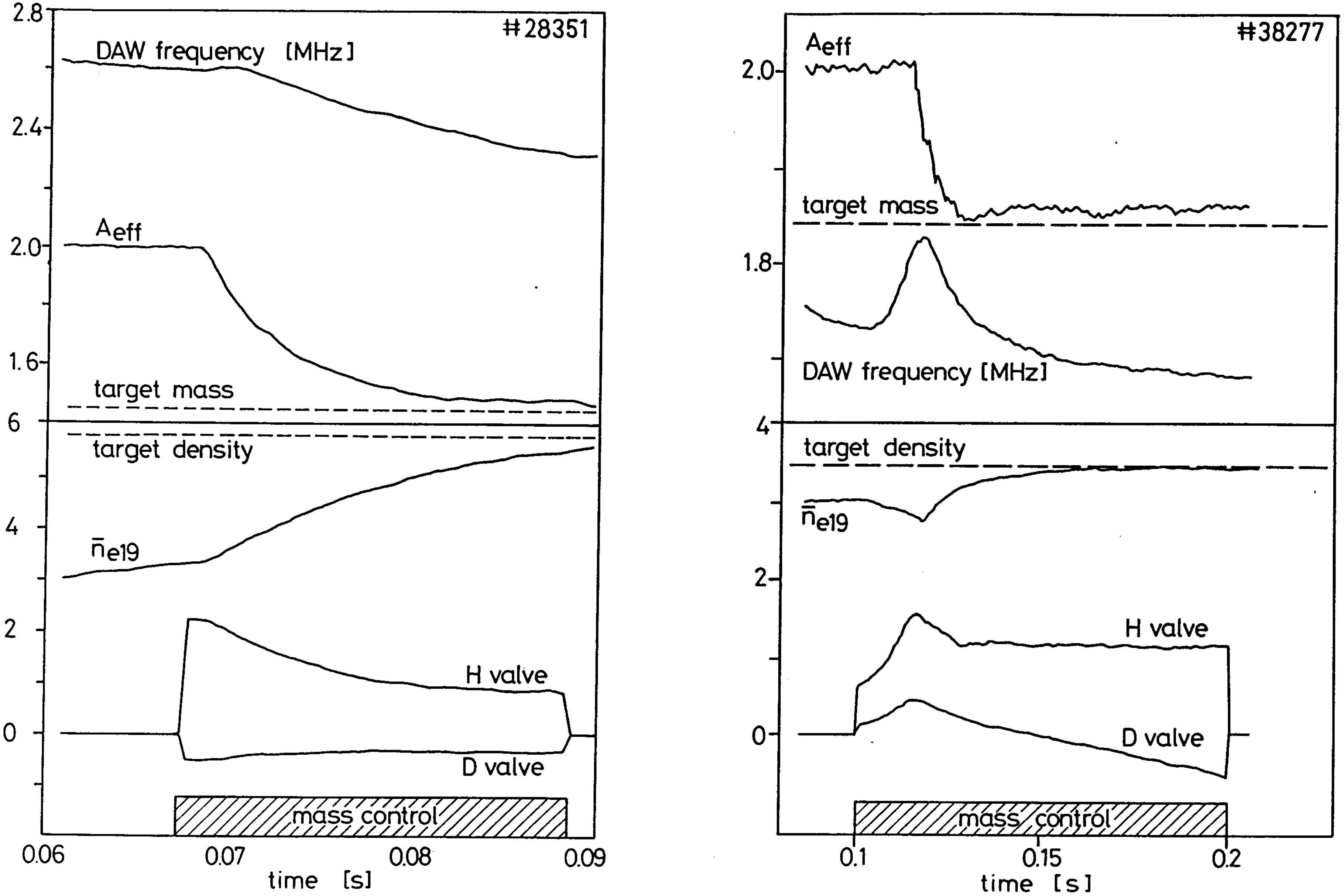

Fig. 6a *Two examples of mass and density feedback control, showing : the DAW frequency, the effective mass, the electron density and the voltages applied on the gas valves.*

6. CONCLUSION

We report the first feedback control of both the electron density and the plasma central effective mass. The latter is measured in real time with a typical error of 3% by frequency tracking a global Alfvén eigenmode. A simple linear feedback control was adequate to control the effective mass with different target values. This system can be used to control D-T mixtures in next generation tokamaks.

ACKNOWLEDGEMENTS

We wish to acknowledge the support of the TCA team in carrying out this study, which was partially funded by the Fonds National Suisse de la Recherche Scientifique.

REFERENCES

1. COLLINS, G.A., HOFMANN, F., JOYE, B., et al, Phys. Fluids **29** (1986) 2260.
2. COLLINS, G.A., HOWLING, A.A., LISTER, J.B., MARMILLOD, Ph., Plasma Phys. Contr. Fusion **29** (1987) 323.
3. WEISEN, H., BORG, G., JOYE, B., KNIGHT, A.J., LISTER, J.B., Phys. Rev. Letters **62** (1989) 434.
4. DESCAMPS, P., VAN WASSENHOVE, G., KOCH, et al, Determination of central plasma parameters on TEXTOR based on Discrete Alfvén Wave spectrum measurements, accepted in Physics Letters A.
5. CHEETHAM, A.D., HEYM, A., HOFMANN, F., et al, Proc. 11th Symp. on Fusion Tech., 1981, Vol. I (1981) 601.