MHD-Mode Locking by Controlled Halo-Current in the T-10 Tokamak

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Abstract. Experiments on a non-disruptive halo-current influence on the m = 2 mode behaviour at the flat-top stage of a tokamak discharge are presented. The halo-current in the *Rail Limiter - Plasma - Vacuum Vessel - External Circuit - Rail Limiter* loop was used. An EMF source controlled with a preprogrammed signal or with a feedback m = 2 signal was introduced into the external part of the halo-current circuit. The EMF source generated oscillating halo-currents with up to 500 A amplitude in the frequency range 0-20 kHz. In the case of the preprogrammed control signal the switching on of the EMF source resulted in the shift of the m = 2 mode frequency to the frequency of the halo-current oscillations. In particular, the rotation of the m = 2 mode stopped under a pulse of zero-frequency halo-current. In the tokamak discharges when the mode rotation stopped by itself before the switching on of the oscillating halo-current, the mode rotation was restored at the halo-current frequency. In the case of the halo-current feedback control by the m = 2 mode signal, the effect depended on the choice of the phase shift in the feedback loop. Some increase or decrease of the m = 2 mode amplitude as well as some variations of the mode frequency were observed at different values of the phase shift. The halo-current effect on the m = 2 mode behaviour can be attributed to a coupling between the m/n = 2/1 magnetic islands and the halo-current magnetic field. The experiment was simulated on the assumption that the tearing mode is affected by the halo-current magnetic field helical component with the same space structure. The equation for the disturbed poloidal flux in the presence of the external helical surface current was used for the analysis. In the calculations for the T-10 conditions, the mode behaviour under the effect of the halo-current was similar to the experimental observations.

1. Introduction

The interaction of tearing modes and externally applied resonant magnetic perturbations has been extensively studied theoretically and has been the subject of experiments on several tokamaks. In the experiments, the resonant magnetic perturbations were usually generated by special windings. The possibilities of feedback stabilisation and locking of the tearing modes were demonstrated in these experiments [1 - 4].

Under some conditions MHD phenomena, especially disruptions in vertically elongated tokamaks, are accompanied by the generation of halo-currents flowing in the plasma along the magnetic field lines between electrically conducting plasma facing components such as the limiter, divertor, vacuum vessel, etc. According to measurements, non-disruptive halo-currents of lower amplitudes are also observed even in macroscopically stable tokamak regimes. The halo-current space structure depends on the plasma parameters and magnetic field configuration as well as on the location of the plasma facing components in the halo-current loop. Owing to the halo-current inhomogeneity, the space-resonant component of the halo-current magnetic field can couple with the tearing-mode magnetic structure. This gives a possibility to use halo-currents to control the frequency and amplitude of MHD-modes in the plasma.

An interdependence of halo-current and m = 2 MHD-mode has been observed in previous T-10 experiments [5]. Under some conditions, switching on of the connector in the external circuit between rail limiter and vacuum vessel resulted in the generation of an oscillating halo-current and a decrease of the m = 2 mode frequency. The frequency of the halo-current oscillations was equal to the m = 2 mode frequency. The new T-10 experiments on active drive of the m = 2 mode by a controlled non-disruptive halo-current at the flat-top stage of the tokamak discharge are presented in this paper. As in our previous experiments, the rail limiter and vacuum vessel have been used as electrodes to introduce the halo-current into the plasma. In this case a controllable EMF source was introduced into the external part of the halo-current circuit.

We assume that in the T-10 experiments the halo-current flowed at the plasma boundary from the rail limiter along the magnetic field lines with some leakage to the vacuum vessel wall due to the SOL plasma perpendicular conductivity. This leakage gives the effective length of the halo-current path in the plasma. The dimensions of this path in the poloidal and toroidal directions in comparison with the corresponding wavelengths of the m/n = 2/1 mode determined the coupling between the halo-current and tearing mode.

2. Experimental Arrangement

T-10 is a tokamak with a circular plasma cross-section. The major and minor radii of the vacuum vessel are R = 1.5 m and b = 0.39 m, the radius of the permanent circular limiter electrically connected to the vacuum vessel wall is 0.33 m. The experiments were carried out at the discharge parameters: toroidal magnetic field B_T = (2.42-2.5) T, discharge current I_P = (240-250) kA. The plasma minor radius determined by the position of the movable rail limiter was a = 0.27 m. A regime with a stationary m = 2 mode of about $5{\cdot}10^{-4}$ T amplitude and approximately 1 kHz frequency was chosen for the experiments.

The structure of the MHD perturbation was measured with poloidal magnetic field sensors located at the inner surface of the vacuum vessel wall. The MHD signal processing procedure included spatial and time Fourier transforms.

The external part of the halo-current loop between the rail limiter and the vacuum vessel was supplied with a final amplifier (FA) which was used as the controllable EMF source and with a shunt for the halo-current measurements (FIG. 1). The FA power supply was switched on at a preprogrammed moment of the tokamak discharge. The FA could generate halo-currents with up to 500 A amplitude in the frequency range 0-20 kHz. The discharge of the FA power

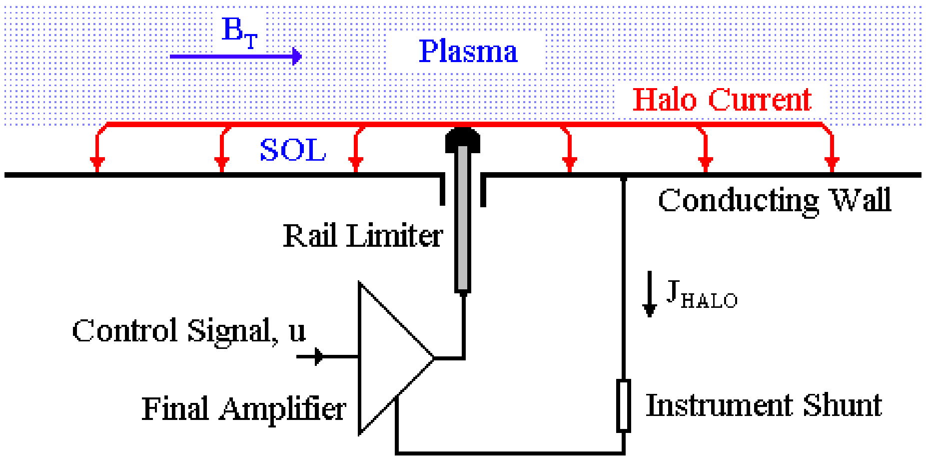

FIG. 1. Halo-current loop: rail limiter - plasma - conducting vacuum vessel wall - instrument shunt - final amplifier - rail limiter.

supply capacitor resulted in a time decay of the halo-current amplitude. Two types of control signals were used in the experiments. In the first set of experiments, the FA input control signal was formed as an independent signal with a preprogrammed time variation of frequency. In the second set of experiments the control signal was formed by a feedback circuit from the signals of the MHD magnetic detectors.

3. Experimental Results

3.1. Preprogrammed Control Signal

In the case of a preprogrammed FA input control signal of a certain frequency, a halo-current of the same frequency was generated after switching on of the FA power supply. In this case the m = 2 mode frequency changed to the value of the halo-current frequency if the control signal and corresponding halo-current amplitudes were sufficiently high. If the control signal frequency varied in time, the m = 2 mode frequency followed the halo-current frequency variation. This result is illustrated in FIG. 2, where the case of a sawtooth-form variation of the control signal frequency is shown. In this figure, the Δt_1, Δt_2 and Δt_3 time intervals are shown with vertical dashed lines. The Fourier spectra of the m = 2 mode signals calculated in these time intervals are given in FIG. 3. The different frequency signs correspond to different rotation directions of the m = 2 mode travelling components; the positive frequency corresponds to rotation in the direction of the electron diamagnetic drift. In FIG. 3 one can see that the main direction of the mode rotation does not change under the frequency variations driven by the halo-current.

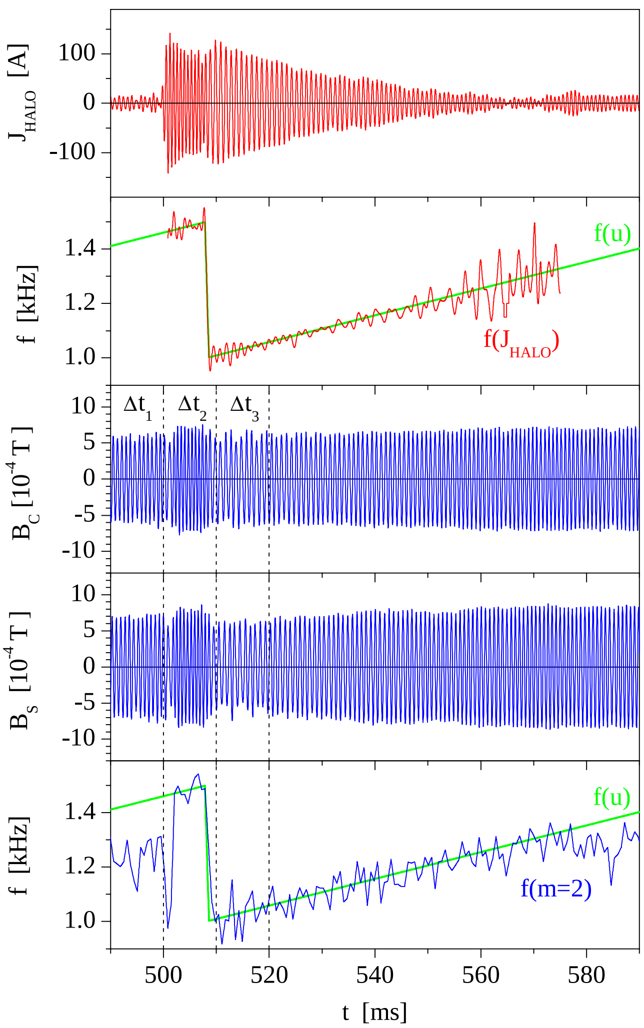

FIG. 2. Variation in time of the m=2 mode frequency under the influence of the oscillating halo-current, J_{HALO}. B_C and B_S - cosine and sine space components of the m=2 mode. The frequency of the control signal, f(u), is shown together with the halo-current frequency, $f(J_{HALO})$, and the m=2 mode frequency, f(m=2). The FA power supply was switched on at t=500 ms.

In the case of a zero-frequency control signal, the rotation of the m = 2 mode stopped under a pulse of direct halo-current (FIG. 4).

In the next experiment a tokamak regime was chosen in which the mode rotation stopped by itself before the switching on of the FA power supply. In this regime the mode rotation was restored to the control signal frequency under influence of an oscillating halo-current (FIG. 5). The Fourier spectrum of the m = 2 signal after the switching on of the FA power supply for the case of FIG. 5 is shown in FIG. 6. In this figure one can see that the m = 2 mode component propagating in the direction of the electron diamagnetic drift predominates over the standing wave component.

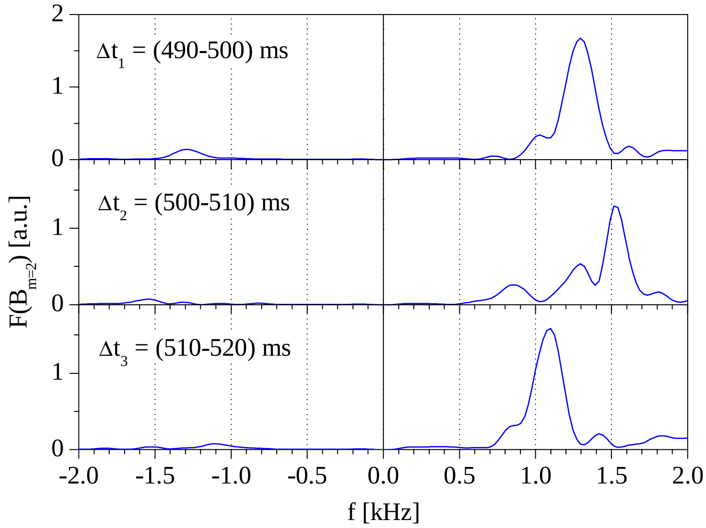

FIG. 3. Fourier spectra of the m=2 mode signals in the Δt_1, Δt_2 and Δt_3 time intervals. The positive frequency corresponds to mode rotation in the direction of the electron diamagnetic drift.

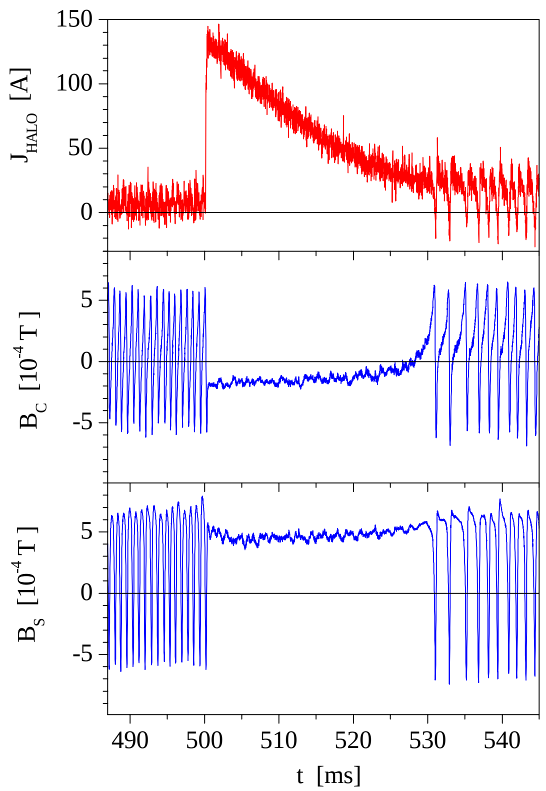

FIG. 4. Termination of the m=2 mode rotation under the influence of a direct halo-current pulse, J_{HALO}. B_C and B_S are the cosine and sine space components of the m=2 mode.

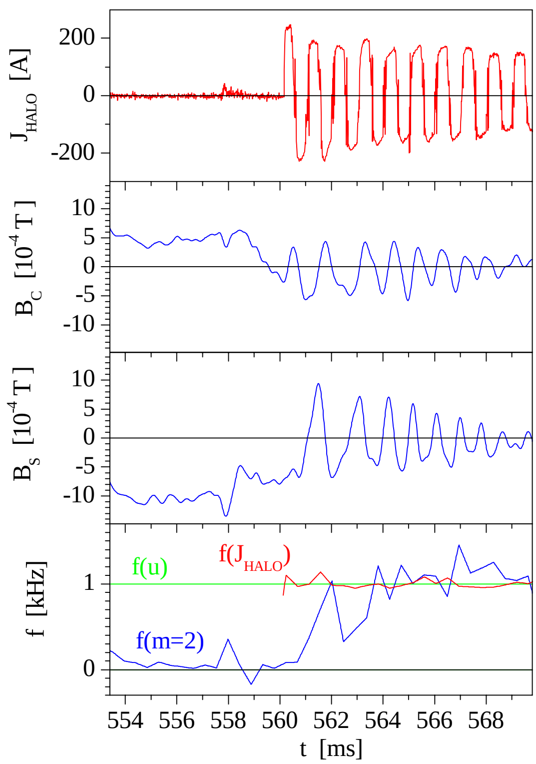

FIG. 5. Restoration of the m=2 mode rotation under the influence of an oscillating halo-current, J_{HALO}. B_C and B_S are the cosine and sine space components of the m=2 mode; f(u) - control signal frequency, f(J_{HALO}) - halo-current frequency, f(m=2) - mode frequency. The FA power supply was switched on at t=560 ms.

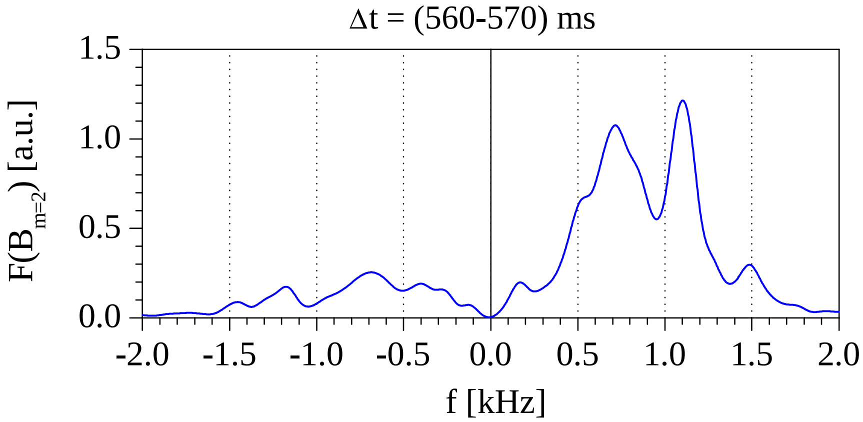

FIG. 6. Fourier spectrum of the m=2 mode signals calculated in the Δt=(560-570)ms time interval for the tokamak discharge shown in FIG. 5. The positive frequency corresponds to mode rotation in the direction of the electron diamagnetic drift.

3.2. Feedback Control Signal

If the control signal at the input of the FA was produced by a feedback circuit from the m = 2 mode signal, the effect of the halo-current on the mode behaviour depended on the choice of the feedback phase shift. In FIG. 7 one can see variations of the m = 2 mode amplitude and frequency observed for opposite values of the feedback phase. In this case the time derivative signal of the m = 2 mode sine space component was used for the control signal formation. The absolute value of the feedback coefficient, K_{FB}, was 24 A·s/T just after the switching on of the FA power supply and degraded to zero along with the discharge of the power supply capacitor.

Some variations of the electron temperature at plasma periphery accompanied the changes of the mode amplitude (FIG. 8). The electron temperature increased in case of the mode suppression and decreased in the opposite case.

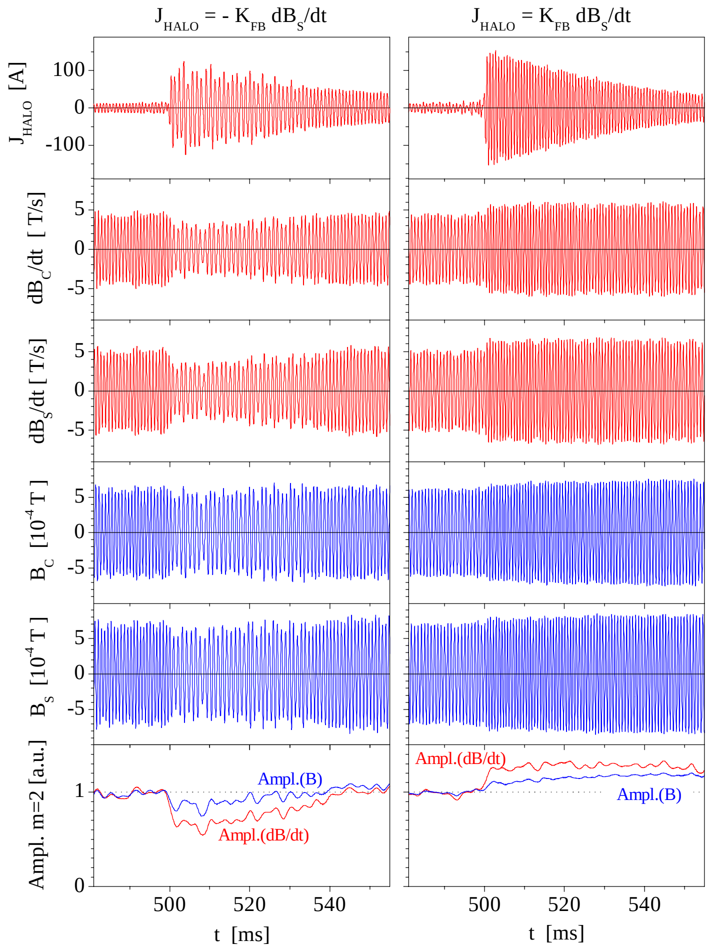

FIG. 7. The m=2 mode behaviour under the influence of the halo-current, J_{HALO}, controlled by the feedback circuit in cases of two opposite phases of the control signal. The amplitudes of the m=2 poloidal magnetic field perturbation, Ampl.(B), and its time derivative, Ampl.(dB/dt), are shown in the bottom panels. The FA power supply was switched on at t=500 ms.

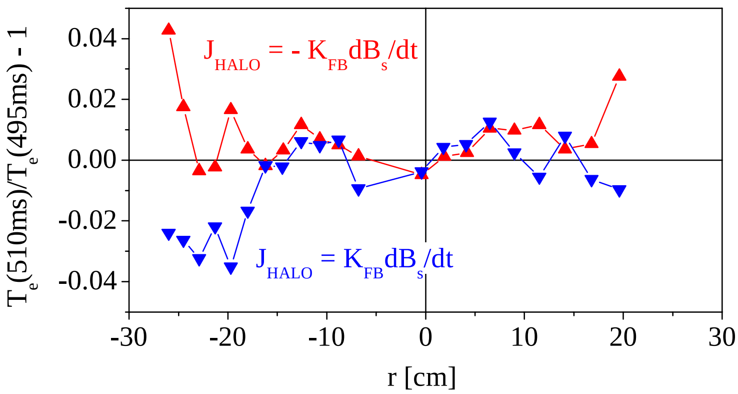

FIG. 8. Relative variations of the electron temperature after switching on of the feedback controlled halo-current for two feedback phases shown in FIG. 7.

4. Numerical Modelling

The T-10 experiments were simulated using the model of the Rutherford non-linear tearing mode [6, 7] interacting with the halo-current helical component with the same poloidal, m, and toroidal, n, numbers. We assumed that this externally controlled current is localised at the plasma boundary surface with minor radius r = a. The equations

$$\frac{\partial}{\partial r}\left(r\frac{\partial\Psi_C}{\partial r}\right)-\left(\frac{m^2}{r}+\frac{\mu_0 R}{B_T}\frac{\partial j/\partial r}{\mu(r)-n/m}\right)\Psi_C+\mu_0 r\cdot\iota\delta(r-a)=0,$$

$$\frac{\partial}{\partial r}\left(r\frac{\partial\Psi_S}{\partial r}\right)-\left(\frac{m^2}{r}+\frac{\mu_0 R}{B_T}\frac{\partial j/\partial r}{\mu(r)-n/m}\right)\Psi_S=0$$

for radial distribution of the cosine, Ψ_C, and sine, Ψ_S, components of the poloidal magnetic flux perturbation, $\Psi(r,\theta,t)=\Psi_C(r,t)\cos(m\theta)+\Psi_S(r,t)\sin(m\theta)$, satisfying the boundary conditions $\Psi_{C,S}(0) = \Psi_{C,S}(b) = 0$, were used for calculations of the cosine and sine components of the stability parameter:

$$\Delta'_{C,S}=\frac{\Psi'_{C,S}(r_S+W/2)-\Psi'_{C,S}(r_S-W/2)}{\Psi_{C,S}},\ \text{where}\ W=4\sqrt{\frac{\sqrt{\Psi_C^2+\Psi_S^2}}{(-rB_T\mu'/R)}}\Bigg|_{r_S}$$

is the width of the magnetic island. In these equations, j(r) is the plasma current density, $\mu(r) = 1/q(r)$, q(r) is the safety factor, r_S is the radius of the resonant magnetic surface, where q = m/n, and ι is the space amplitude of the external current surface density at r = a, which is assumed to be proportional to cos(mθ). The value of the external current is $J=2a\cdot\iota/m$.

The system of two equations

$$\frac{\partial\Psi_C}{\partial t}=\pi a^2\omega_R\frac{\Delta'_C(W)}{W}\Psi_C-\Omega\Psi_S,$$

$$\frac{\partial\Psi_S}{\partial t}=\pi a^2\omega_R\frac{\Delta'_S(W)}{W}\Psi_S+\Omega\Psi_C$$

was used for modelling the rotating tearing mode behaviour in time. In these equations, Ω is the mode natural frequency, $\omega_R = 1/\tau_R$, where τ_R is the resistive time. The external helical current influences non-linearly both space components of the perturbation because variations in time of the external current, J, cause variations of Δ'_C that produce changes in W and hence in Δ'_S.

The time evolutions of the cosine, $B_C = \partial\Psi_C/\partial r$, and sine, $B_S = \partial\Psi_S/\partial r$, components of the m/n = 2/1 poloidal magnetic field perturbation at r = b were calculated for the conditions of T-10 experiments. The plasma current profile was selected to produce the saturated m = 2 mode amplitude of $5\cdot10^{-4}$ T without the external helical current. The resistive time was chosen as $\tau_R = 0.01$ s. The simulation of the experiments on halo-current control by the preprogrammed control signal is presented in FIG. 9. The pulses of oscillating and direct external helical current, J, were applied to the m = 2 mode, which was initially oscillating with $\Omega/2\pi = 1$ kHz frequency. The application of the current oscillating with a frequency of 1.5 kHz resulted in the mode frequency shift to the external current frequency. In the case of the direct current pulse, the mode rotation stopped for the pulse time period.

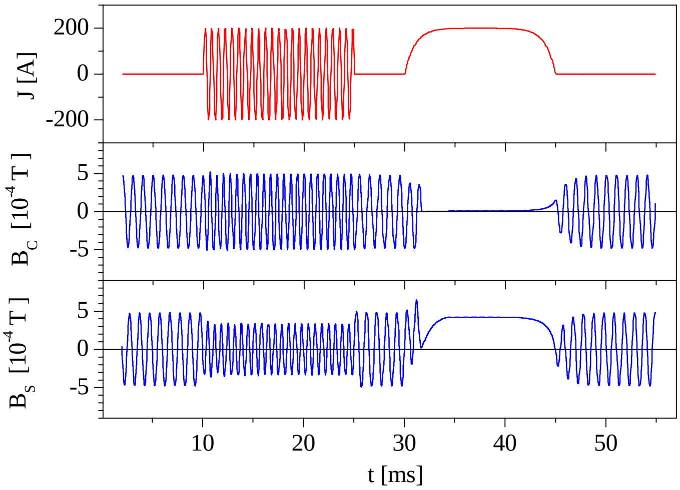

FIG. 9. Simulation of the effect of a preprogrammed external helical current on the behaviour of the non-linear tearing mode.

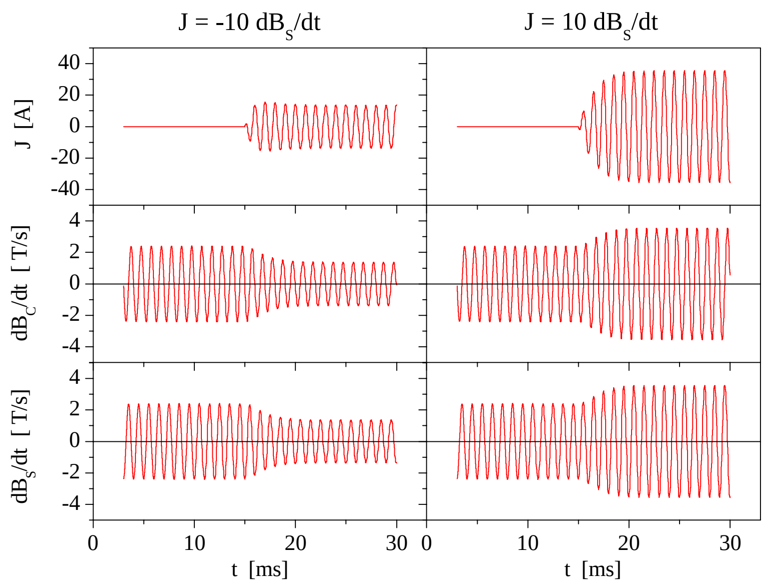

FIG. 10. Simulation of the effect of a feedback controlled external helical current on the behaviour of the non-linear tearing mode.

In the simulation of the feedback experiment the external helical current was set proportional to dB_S/dt. In cases of two different signs of the proportionality coefficients, the switching on of the external helical current at t = 15 ms resulted in a decrease and an increase of the mode amplitude (FIG. 10). In FIG. 9 and FIG. 10 one can see that the calculated behaviour of the m = 2 mode in the presence of the helical current at the plasma boundary is similar to the experimental behaviour of the m = 2 mode driven by the halo-current. In simulations, the mode frequency variations were obtained without any changes of the mode natural frequency. As in [4], the frequency variations can be attributed to the well known effect of the frequency locking in an externally driven non-linear oscillator. In the general case the oscillations can be considered as a superposition of natural and forced oscillation components. In the case of sufficiently high amplitude of the forced component, the component with the natural frequency can be converged due to the non-linear damping.

5. Conclusions

It can be concluded that halo-current affects the behaviour of the tearing mode in a tokamak plasma. This effect can be attributed to a coupling between the mode magnetic structure and the space resonant component of the halo-current magnetic field. This should be taken into account in considerations of MHD phenomena, especially at a high level of halo-current in the case of disruptions in vertically elongated tokamaks. Under appropriate conditions, externally controlled halo-currents can be utilised to control the frequencies and amplitudes of MHD modes.

Acknowledgements

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References

[1] Bol K., et al., “Experiments on the Adiabatic Toroidal Compressor”, Plasma Physics and Controlled Nuclear Fusion Research (Proc. 5th Int. Conf., Tokyo, 1974), IAEA, Vienna (1975) **1**, pp. 83-97.

[2] Arsenin V.V., et al., “Feedback Stabilisation of Kink Instability in the TO-1 Tokamak”, Plasma Physics and Controlled Nuclear Fusion Research (Proc. 7th Int. Conf., Innsbruck, 1978), IAEA, Vienna (1979) **1**, pp. 233-245.

[3] Morris A.W., et al., “Feedback Stabilisation of Disruption Precursor Oscillations”, Controlled Fusion and Plasma Physics (Proc. 16th European Conf., Venice 1989), EPS (1989) **2**, pp. 541-544.

[4] Ivanov N.V., Kakurin A.M., “Frequency Locking of Helical Perturbation in a Tokamak”, Fiz. Plazmy **5** (1979) 969 [Sov. J. Plasma Phys. **5** (1979) 541].

[5] Ivanov N.V., et al., “Interdependence of Magnetic Islands, Halo Current and Runaway Electrons in T-10 Tokamak”, Fusion Energy 2000 (Proc. 18th Int. Conf., Sorrento, 2000), IAEA, Vienna (2001) CD-ROM file EXP2/02.

[6] Rutherford P.H., “Nonlinear growth of the tearing mode”, Phys. Fluids **16** (1973) 1903.

[7] White R.B., et al., “Saturation of the tearing mode”, Phys. Fluids **20** (1977) 800.