Analysis methods and conditions for feedback controlled NTM stabilization

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Introduction

The occurrence of neoclassical tearing modes (NTM) leads to creation of magnetic islands with subsequent increase of radial heat transport, confinement degradation and $\beta = p/(B^2/2\mu_0)$ limit [1]. It has been shown that the NTM can be suppressed and completely stabilized with electron cyclotron current drive (ECCD) and $\beta$ can be increased after the stabilization [2]. However the stabilization is very sensitive to the match of radial positions of the NTM and the ECCD deposition. The increase of beta due to mode stabilization usually leads to a mismatch of the positions due to the Shafranov shift and as a result the NTM can grow again.

This situation can be avoided by feedback control of the ECCD deposition. In general this problem can be divided in two tasks: Real-time NTM radial position determination and allocation of ECCD deposition at the same position. Previously feedback controlled NTM stabilization has been demonstrated in DIII-D by control of the Mirnov signal amplitude [3] and in JT-60U with NTM position determination based on $T_e$ standard deviations and ECRH deposition calculation by real-time plasma shape reconstruction [4]. However the first method needs for each iteration a time interval of about 100 ms for checking whether the mode amplitude decreases or not, the second method has relative big noise in the NTM detection part and doesn’t measure the actual ECRH position. Our approach is to detect both the NTM position and the position of ECCD deposition separately and to steer the ECCD position in order to reduce the distance between the positions. The present paper concentrates on the position determination methods.

Methods and experiment

In ASDEX Upgrade several experiments for the determination of NTM position and ECCD deposition have been done. Electron cyclotron emission (ECE) detected with a 60 channel heterodyne radiometer is used as the main diagnostic. The video signal of each radiometer channel corresponds to the electron temperature at the defined radial position. The diagnostic allows to obtain the time evolution of the electron temperature profile with a spatial resolution of 1 – 2 cm and with a sampling rate 32 kHz.

For the determination of the NTM position the temperature oscillation due to the rotation of the magnetic island is filtered by correlation of the ECE radiometer signals with a reference signal from one of the Mirnov coils. The coil position is chosen for zero phase difference with the radiometer signals. After downconversion to near zero frequency and low pass filtering the time evolution of the correlation signal for each ECE radiometer channel is obtained. This correlation signal vanishes if there is no temperature oscillation at the corresponding radial position at the mode frequency, otherwise the absolute value of the signal is proportional to the temperature oscillation amplitude. Temperature oscillations in phase and in antiphase with the magnetic
perturbation signal lead to different signs of the signal. Taking into account that the
temperature oscillations phase is changed by $\pi$ inside the island and assuming that the
biggest oscillations at this frequency are produced by the NTM, the NTM position is
obtained as the zero transition between two biggest extrema[fig 1B] in the correlation
function profile.

For the determination of the position of ECCD deposition modulated ECCD with
90% duty cycle is used. This value of the duty cycle has been chosen as a compromise
between the conflicting objectives of maximum average ECRH power to suppress the
mode and sufficient spectral power to detect the temperature oscillations. The ECCD
deposition radius can be found as the point of maximum modulated electron temper-
ature amplitude and minimum phase at the modulation frequency. The ECRH power
signal provides the modulation frequency, duty cycle and the phase of the ECRH power
waveform. The detection occurs with an iteration algorithm. As a first approximation,
the deposition location is calculated with the TORBEAM code [5] for the first time
point and for each successive time point the result for the previous one is taken. Because
of heat diffusion the phase difference between the ECRH power waveform and the tem-
perature oscillation signal at the deposition radius varies in the range of $\pi/4 - \pi/2$ [6],
so that as second step the sine signals with a $\pi/4$ phase shift at the modulation and har-
monics frequencies are formed. The second position approximation for each harmonic
is found as the point of maximum correlation of the sine and ECE radiometer signals,
which is closest to the position found in the first approximation. The final position is
de fined as the averaged point of the positions in the second approximation. The second
possibility is to define the final position as averaged position of harmonics correlation
function first derivative zero transition.

In experiments for the simultaneous determination of both NTM position and ECCD
deposition discharges were made in lower single null configuration in the ELMy H-mode
regime. At a line averaged density $n_e = 5 \cdot 10^{19}$ m$^{-3}$ 10 MW of NBI heating power was
injected. Fig. 1A illustrates the discharge, where the (3,2) NTM is suppressed but not
completely stabilized by feed forward variation of the radial position of ECCD deposition
with a toroidal magnetic field $B_t$ ramp. Fig. 1A shows the traces of radial positions of
the NTM (blue), ECRH deposition detected as the correlation function maximum (red),
ECRH deposition detected as position of correlation function first derivative zero transi-
tion (green) and simulated ECRH deposition radius (black) to compare it with the mea-
sured values, in the bottom graphs the applied heating power (NBI, ECRH), the Mirnov
coil magnetic perturbation signal, the variation of $B_t$ and $\beta_N = \beta/|I_p/Ma|/a[B/T]$ are
given. The simulation of the ECRH position (black curve fig. 1A) is done taking
into account the first absorption position, calculated with TORBEAM code, the ab-
sorption position evolution with the toroidal field change and the observed position to
absorption position relation due to the equilibrium change. In the discharge the NTM
arises at $t = 2$ s and $\beta_N$ degrades immediately. The NTM position detection is wrong
because of ECE cut-off before $t = 2.1$ s. At $t = 2.15 - 2.3$ s the NTM position moves
inward and at $t = 3.1 - 3.3$ s outward in the plasma due to a change of the Shafranov
shift. At $t = 2$ s 1.4 MW of modulated ECCD power is applied. The observed jumps
in the position of ECRH deposition 1 (fig. 1A, red curve) can be explained by the fact
that this position is found as a maximum of the correlation function profile and this
maximum is associated with an individual ECE radiometer channel at a time. At the
ECCD position the spatial radiometer resolution is $\approx 2$ cm, for the further experiments
it can be improved to $\approx 1$ cm by the choice of radiometer settings. Nevertheless the
ECCD position can be observed. As the EC resonance is slowly moved towards the mode position at \( t = 2.0 - 3.1 \) s, the mode amplitude decreases. Then NBI heating power is increased up to 12 MW and the positions diverge because of the Shafranov shift. The mode amplitude increases again.

**Advantages and limits**

The method of the NTM position determination by correlation analysis has an advantage in comparison with FFT analysis and with the method of standard deviations \[4\]. Our method has a calculation time proportional to \( N \), the standard radiometer deviation calculation time is also proportional to \( N \), while the FFT processing time is proportional to \( N \log_2 N \), where \( N \) is the number of time points for each time interval. Another factor is the signal to noise ratio (SNR). The standard radiometer deviation method takes into account the entire radiometer video bandwidth \( \Delta f_v \), the FFT amplitude reduces the video bandwidth to \( \Delta f_{fft} = 1/\Delta t \), where \( \Delta t \) is the duration of the analysis time interval. Because of the defined phase the correlation analysis has SNR by factor of \( \sqrt{2} \) better than FFT, which is by factor of \( \sqrt{\Delta f_v/\Delta f_{fft}} \) better than standard deviation method. The method of ECCD deposition detection by correlation with the ECCD power waveform has an advantage that the phase and the amplitude information of several harmonics is
used simultaneously.

The SNR and precision of the ECCD position detection depends on the modulated electron temperature amplitude and heat diffusivity. The effectiveness of the detection can be regulated by the choice of ECCD power, modulation frequency and duty cycle. Thus the limits and optimal conditions have to be studied. The NTM usually develops on a timescale of 100 ms. For the position measurement at least 4-10 modulation pulses are necessary. It means that the modulation frequency can not be less than 40 – 100 Hz. On the other hand, the modulated electron temperature amplitude is found to be decreasing with increasing of the modulation frequency and is limited by the SNR. There are three main noise sources in this frequency range: Plasma noise, ELMs and sawteeth. The plasma rms noise can be evaluated with the radiometer formula as

$$\Delta T = T_e / (\sqrt{\Delta t_{eccd} \cdot \Delta f_{RF}}),$$

where $T_e$ is the measured electron temperature (as a typical example $T_e \approx 2$ keV), $t_{eccd}$ is the time interval of ECCD detection and $f_{RF} = 300$ MHz is the RF bandwidth. Assuming ideal conditions: 50% duty cycle, $t_{eccd} = 50$ ms - one half of the NTM development time, other noise sources absence and taking the requirement of third harmonic presence at SNR $> 2$, the relation $T_{e3} = T_{e1}/3 > 2\Delta T$, where $T_{e1}$ and $T_{e3}$ are the amplitudes of the electron temperature oscillation at the fundamental frequency and at the third harmonic frequency respectively, is resulted. Hence the requirement is $T_{e1} > 3$ eV. The modulated electron temperature amplitude at $f_{mod} = 250$ Hz was measured to be $\approx 5$ eV at the 50% duty cycle and ECCD power 1.2 MW, so $f_{mod} = 250 – 300$ Hz can be fixed as the upper limit. In experiments Type I ELMs were found to be most dangerous noise source for the measurements. Improved techniques to avoid this noise are being studied.

Conclusions

In this paper the two analysis methods for the NTM position and the position of ECCD deposition determination are reported. Both techniques can be used for the feedback controlled NTM stabilization. The advantages in comparison with the FFT analysis and with the method of the standard radiometer deviations evaluation are shown. The results of the simultaneous positions detection and the dependence of suppression effectiveness on the positions match are demonstrated. Optimal conditions for ECCD modulation are studied.

References

[6] Leuterer, F. et al.: Modulated ECRH power deposition in ASDEX Upgrade, accepted for publication in Nucl. Fusion