Mode rigidity study of RWM on RFX with reduced RWM control coils for JT-60SA RWM stabilization

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To achieve a steady-state high beta plasma, suppression of resistive wall mode (RWM) is necessary because the no-wall beta limit of a steady state plasma with a large bootstrap current fraction is relatively low. Basically, there are two procedures to stabilize RWM. One is stabilization by plasma rotation and the other is feedback stabilization with active control coils. From the point of view of technical design, stabilization by rotation is preferable to that obtained with in-vessel control coils, however recently it was reported that RWM is sometimes triggered even with sufficient rotation by ELM, Fishbone, Energetic particle driven Wall Mode and other events [1]. Therefore, an RWM active control system for JT-60SA is being designed [2], in order to achieve a steady-state high beta plasma and also to clarify the stabilization mechanism of RWM to be extrapolated toward ITER and DEMO. The target normalized beta (β_N) of JT-60SA steady state plasma is β_N = 3.5-5.5, exceeding no-wall beta limit and the plasma will be sustained for 100s.

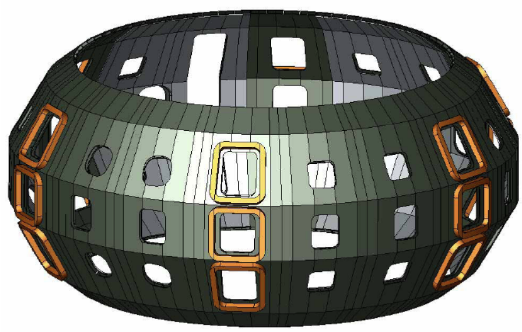

Fig. 1 Schematic drawing of RWM control coils with stabilizing plate.

Figure 1 shows RWM control coils with the stabilizing plate. RWM control coil consists of 3 coils in the poloidal direction and 6 poloidal arrays in the toroidal direction. Therefore Total number is 18. Each coil has eight turn conductors, and maximum current is 2.5kA. This corresponds to 20 kAT. Figure 2 shows the cross-section of the RWM coil. We have a plan to use mineral

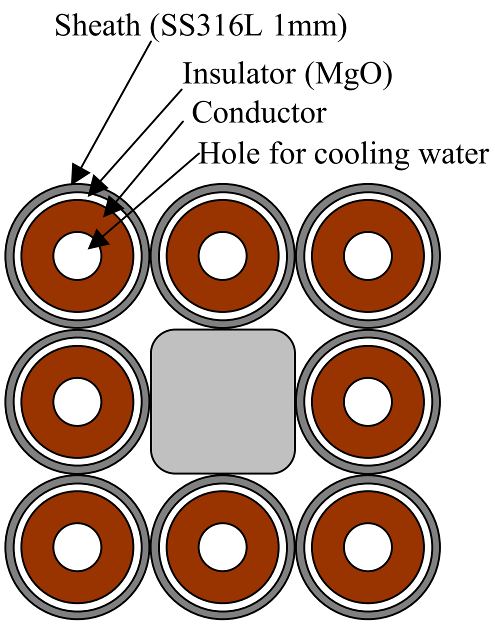

Fig. 2 Cross-section of the RWM coil with eight turn MICs.

insulation cable, which is being developed by ourselves, as the conductor of the RWM coil.

We performed RWM feedback control simulation for n=1 mode with VALEN code [3] in order to evaluate the achievable beta value [4]. The high beta value β_N = 4.35 was expected and obtained value of C_β = 0.9 means that efficient control will be expected for the steady state plasma with no-wall beta limit $\beta_N^{no\text{-}wall}$ =3.12 and ideal-wall beta limit $\beta_N^{ideal\text{-}wall}$ = 4.49, where $C_\beta = (\beta_N - \beta_N^{no\text{-}wall})/(\beta_N^{ideal\text{-}wall} - \beta_N^{no\text{-}wall})$. The pressure and current profiles are consistent with the ACCOME analysis [5]. The target steady state JT-60SA plasma is now being developed. Figure 3 shows the latest example of high beta steady state plasma obtained with the ACCOME code.

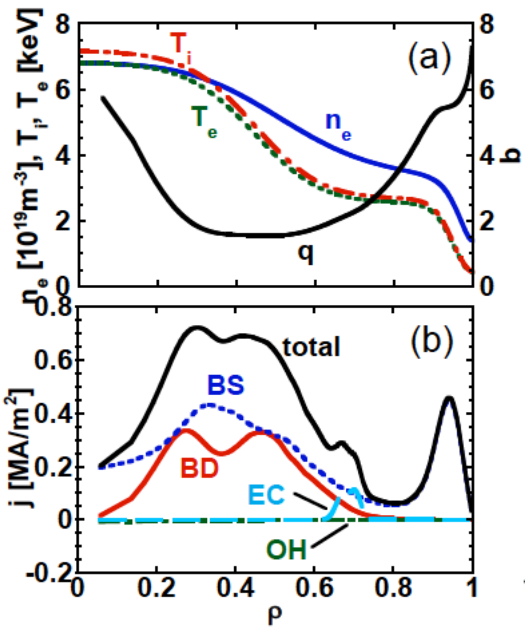

Fig. 3 Profiles of high beta steady-state plasma. (a) Electron and ion temperature (T_e, T_i), electron density (n_e) and safety factor (q). (b) Total plasma current (total), bootstrap current (BS), beam driven current (BD), electron cyclotron driven current and ohmic current.

The maximum current of RWM control coils calculated with VALEN is about 1.7 kAT. This value is much smaller than Maximum designed current of 20kAT for control coils. These results seem to be optimistic because, the VALEN simulation was performed with no sheath effect, simple 1 turn coil, no time delay of calculation and power supply and no noise. It employs the least stable plasma eigenfunction, assuming a rigid plasma perturbation mode structure. For instance, the coil current requirement increase from 1.7 kAT to ~12 kAT, if added 1ms time delay.

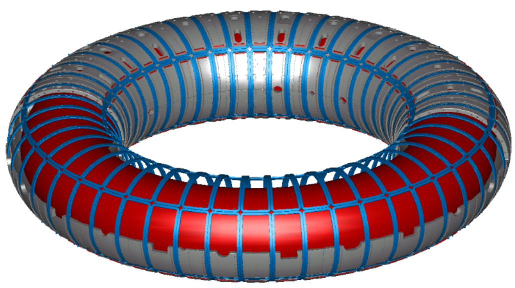

Fig. 4 . RFX-mod active coils. Each coil has an independent amplifier.

The problem of mode-rigidity is very important for JT-60SA, because the coverage area of plasma surface with coils is very small as shown in Fig. 1, and much smaller than existing systems (DIII-D, NSTX, RFX, …). There are two issues connected to mode non-rigidity. One is mode deformation and the other is the destabilization of side-band modes, which are marginally stable without mode control . We performed some experiments on the RFX-mod device [6] implementing a novel control software that for the first time allows to act with a reduced sets of coils only on selected modes [7]. The new software has been developed explicitly to perform studies on mode deformation and sideband generation when using different coil configurations on the same machine. The RFX-mod is fully covered by the active control coils, which consist of 4 coils in the poloidal direction (top, bottom, inside and outside) and 48 in the toroildal direction, total 192 coils, as shown in Fig. 4. Each coil has an independent amplifier and successfully controls RWMs and TMs. We have tried to suppress the most unstable RWM (m=1,n=-6) with reduced number of coils. Table 1 shows the coil configurations on RFX for this experimental campaign, the unstable mode and coverage rate of coils to plasma surface, also those of JT-60SA are shown. We decrease the coil numbers from 192 to 8, which is corresponding to the coil coverage from 100% to 4.2%. Coil coverage of JT-60SA is ~7%. Figure 5 shows the temporal evolution of m=1,n=-6 RWM amplitude. RWMs are stabilized with only eight coils without stabilization of some sideband modes. For instance, if we use the eight coils in the toroidal direction for stabilize m=1, n=-6 mode, the coils induce m=1, |n|=2, 10, 14, 18, 22 sideband modes. RFX-mod can perform a certain RWM

Machine	Most unstable RWM	Number of coils (poloidal)	Number of coils (toroidal)	Coverage
RFX	m=1,n=-6	4	48	100%
		1 (top)	48	25%
		1 (top)	24	12.5%
		1 (top)	16	8.3%
		1 (top)	12	6.25%
		1 (top)	8	4.2%
		4	3	6.25%
JT-60SA	m=3,n=1*	3	6	6.8%

Table 1 Reduced coil configurations for RWM stabilization experiment on RFX-mod, most unstable mode and surface coverage, also those of JT-60SA are shown. *largest poloidal component.

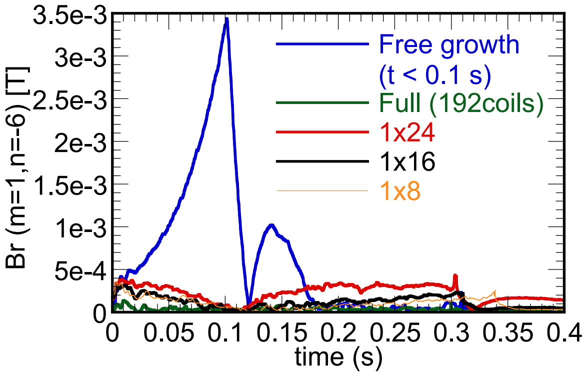

Fig. 5 Temporal evolution of m=1,n=-6 RWM amplitude. RWMs are stabilized with only eight coils without stabilization of sideband modes.

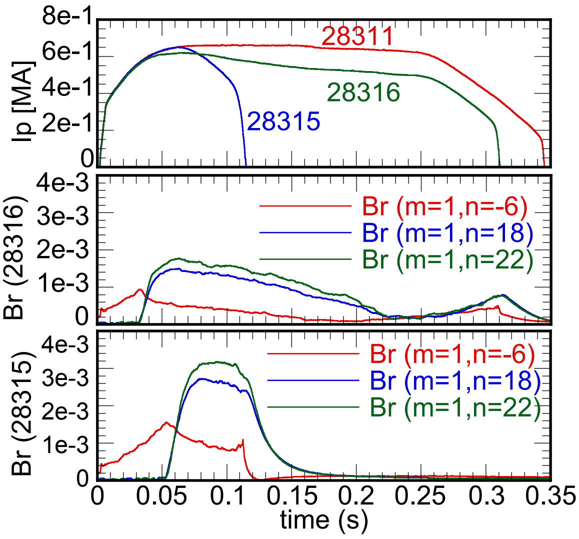

Fig. 6 Temporal evolution of plasma current (upper), stabilized m=1,n=-6 RWM amplitude and m=1,n=18, 22 sideband amplitude of 28316 (middle) and 28315

stabilization with or without sideband stabilization with full coils. Figure 6 shows the effect of sideband mode. On the plasma of 28311, m=1,n=-6 mode and sideband mode are stabilized from the beginning of discharge. On 28315 and 28316, m=1,n=-6 mode are stabilized from 0.03s and 0.05s, respectively, without sideband stabilization. Large m=1,n=18, 22 modes appear and after that plasma current decrease. Finally, plasma was terminated due to large sideband mode on 28315. We have to pay attention to plasma deformation due to large sideband modes induced by small coils.

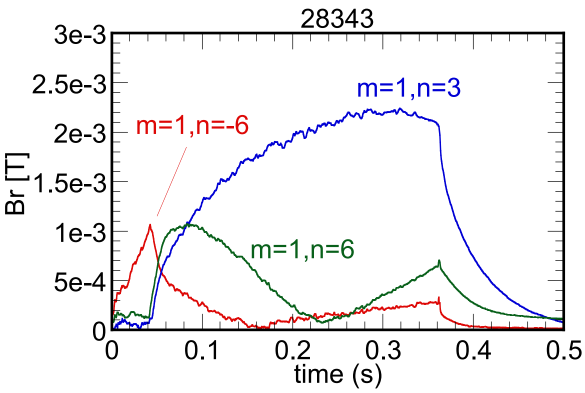

Fig. 7 Temporal evolution of stabilized m=1,n=-6 RWM and m=1,n=3, 6 sideband amplitude. RWM was stabilized with four coils in the poloidal direction and three coils in the toroidal direction.

We observed the destabilization of sideband mode, which is marginally stable without mode control. Figure 7 shows the temporal evolution of stabilized m=1,n=-6 RWM and m=1,n=3, 6 sideband amplitude. RWM was stabilized with four coils in the poloidal direction and three coils in the toroidal direction. Usually, sideband modes amplitude decrease with decrease of stabilized mode as m=1, n=6 mode in Fig.7 and m=1,n=18, 22 mode in Fig.6, because active coil current decreases. However m=1,n=3 mode increase during discharge. The m=1,n=3 mode on the plasmas of this experimental campaign is marginal stable RWM and its growth is a clear exemplification of the so-called resonant field amplification (RFA), due in this case to a sideband generated field.

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