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High current and low q_{95} scenario studies for FAST in the view of ITER and DEMO

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ABSTRACT

The Fusion Advanced Study Torus (FAST) has been proposed as a possible European satellite, in view of ITER and DEMO, in order to: (a) explore plasma wall interaction in reactor relevant conditions, (b) test tools and scenarios for safe and reliable tokamak operation up to the border of stability, and (c) address fusion plasmas with a significant population of fast particles. A new FAST scenario has been designed focusing on low-q operation, at plasma current $I_P = 10$ MA, toroidal field $B_T = 8.5$ T, with a $q_{95} \approx 2.3$ that would correspond to $I_P \approx 20$ MA in ITER. The flat-top of the discharge can last a couple of seconds (i.e. half the diffusive resistive time and twice the energy confinement time), and is limited by the heating of the toroidal field coils. A preliminary evaluation of the end-of-pulse temperatures and of the electromagnetic forces acting on the central solenoid pack and poloidal field coils has been performed. Moreover, a VDE plasma disruption has been simulated and the maximum total vertical force applied on the vacuum vessel has been estimated.

1. Introduction

The FAST device is presently under discussion as a possible DEMO and ITER satellite [1,2]. The main FAST goals are: investigating plasma wall interaction, especially power exhaust problem [3], in reactor relevant conditions; testing tools and scenarios for safe and reliable tokamak operation up to the border of stability, with particular attention on avoiding disruptions; studying fusion plasmas with a significant population of fast particles. The FAST reference scenario, as well as the ITER one, has been designed with q_{95} slightly above three to avoid dangerous MHD activity [4]. JET has shown the possibility to safely work at $q_{95} \sim 2.6$ [5,6] although with a slight degradation of the energy confinement ($H_{98} \sim 0.9$), probably due to fuelling issues and/or lack of additional heating [7]. A new FAST scenario has been designed, focusing on low-q operation, which allows exploring 10 MA plasmas. In particular, we refer to regions with $2 < q_{95} < 2.7$ that are interesting to push fusion performances, but could be too risky to be tested in ITER. The main aim has been to develop some safe and robust tools to mitigate the occurrence of MHD driven disruptions, when operating close to some machine limit, under very large plasma magnetic and kinetic energy density conditions not far from reactors values [8]. Specifically, we investigate a new FAST scenario at $I_P = 10$ MA, $B_T = 8.5$ T, with a $q_{95} \approx 2.3$ that would correspond to $I_P \approx 20$ MA in ITER. Under these conditions FAST – assuming confinement degradation as in JET – could achieve an equivalent fusion gain $Q_{DT} = 3.7$.

The plasma equilibrium configuration will be presented in Section 2. A transport analysis, using GLF23 transport mode will be also discussed in Section 2, confirming the values obtained by the 0D scaling law. A preliminary evaluation of the end-of-pulse temperatures and the vertical forces applied on the vacuum vessel due to a VDE plasma disruption will be shown in Section 3. These preliminary results confirm that this high current scenario is compatible with the current FAST design. MHD stability and the feedback controlled active coils studies will be briefly discussed in Section 4. More details are given in [8]. Finally, Section 5 draws the conclusions.

2. Development of 10 MA scenario

FAST operations are foreseen in a wide range of parameters: from high performance H-mode (toroidal field, B_T, up to 8.5 T; plasma current, I_P, up to 10 MA, as presented here) to advanced

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tokamak (AT) operation (I_P = 3 MA) as well as fully Non-Inductive Current Drive scenario (NICD), with B_T = 3.5 T and I_P = 2 MA [4]. The heating power consists of 30 MW delivered by an Ion Cyclotron Resonance Heating (ICRH) system (30–90 MHz), 4 up to 6 MW by a Lower Hybrid (LH) system (3.7 GHz or 5 GHz) for the long pulse AT scenario, 4 up to 15 MW by an Electron Cyclotron Resonant Heating (ECRH) system (170 GHz to 6 T) for MHD and localized electron heating control and, eventually, 10 MW by Negative Neutral Beam Injection (NNBI), for which the ports design foresees accommodation. For all cases, the geometrical plasma features are major radius R = 1.82 m, minor radius a = 0.64 m, elongation k = 1.7 and triangularity <δ> = 0.4. FAST Poloidal Field Coils (PFCs) system is designed to provide the necessary flux (about 35 V for the reference poloidal currents scenario [4]) and to sustain the high performances H-mode for more than 10 s in the reference scenario with a plasma current of 6.5 MA. The PFCs system includes 6 coils distributed around the plasma chamber and a central solenoid (CS) made of 6 pancakes [9]. The structure of FAST Toroidal Field Coils (TFCs) system has a 20° modular configuration. The TFCs system consists of 18 coils, each of them made of 14 copper plates suitably worked out in order to realize 3 turns in radial direction, with 89.2 kA per turn. The finite number and toroidal extension of the TFCs causes a periodic variation of the toroidal field from its nominal value, called toroidal field ripple (TFR), δ_{BT}. To limit the TFR within acceptable values, ferromagnetic inserts or active coils have been studied [10]. The last analysis on the approach based on active coils are discussed in [11].

The main aim of the new FAST scenario (10 MA/8.5 T) presented here is the preparation of a complete and reliable low q_{95} scenario, ready to be transferred to that already proposed in ITER, with 17 MA and $q_{95} \approx 2.65$, very close to ignition. Consequently FAST could develop some safe and robust tools to mitigate the occurrence of MHD driven disruptions, when operating close to some machine limit, under very large plasma magnetic and kinetic energy density conditions and with dimensionless physics parameters close to DEMO and ITER. It is well known that, lowering the edge safety factor, both the kink and the tearing MHD modes become more unstable [12], hence setting an upper limit to the plasma current in order to avoid dangerous disruptions. However, following a suitable trajectory in the q_{95}-li plane during the plasma current ramp-up, it is possible to reach plasma equilibria at the very low $q_{95} \geq 2$ [12]. This can be even easier in X-point tokamak configurations, thanks to the stabilizing role played by the strong edge magnetic shear. JET experiments [5–7], with $q_{95} \approx 2.6$, have confirmed the possibility to safely work at $q_{95} < 3$ even for large machines at very high plasma current. In addition, other experiments (performed on RFX operated as a Tokamak [13] and recently confirmed by some very preliminary tests on DIII-D [14]) have hinted the possibility of using active coils to control Resistive Wall Mode (RWM) when operating at $q_{95} \approx 2$. These facts have encouraged to study the possibility FAST scenarios at $2 < q_{95} < 2.7$, presented here.

2.1. Plasma equilibrium configurations

A set of equilibria has been studied, corresponding to plasmas with a slight different current profile. These in turn correspond to different stability properties, as detailed in the following. The q profiles for the various equilibria are shown in Fig. 1. The free boundary equilibria have been computed by means of FIXFREE code [29]. The current density profiles are varied to get different pairs of q_{95}–l_i values. The magnetic internal inductance l_i mentioned here is referring to l_i definition discussed in [15]. The Iso–$q(\psi)$ map, q_{95} and $q(\psi)$ = 2 surfaces are shown in Fig. 2. A simplified representation of the conducting structures (blue line) is also reported in Fig. 2. In the insert, the $q_\psi(R)$ profile is reported. The minor plasma

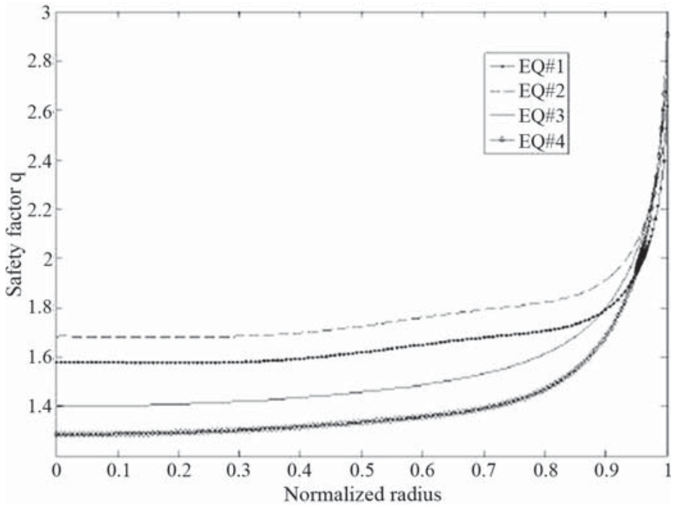

Fig. 1. Safety factor profiles for various equilibria.

radius slightly changes, allowing a variation of q_{95}; accordingly, also the ratio b/a changes ("a" is the minor plasma radius and "b" is the minor radius of the conductive structures). The closeness of the $q(\psi)$ = 2 surface to the plasma boundary suggests a possible interaction of the modes associated with this surface with the FAST conductive structures, and the possibility to stabilize these modes by active coils [8]. As mentioned before, the absence of the $q(\psi)$ = 1 surface is an artefact introduced to allow linear MHD codes to easily study the tearing and external kink instabilities. Four different equilibria have been designed, as detailed in Table 1.

The equilibrium parameters have been modified keeping in mind the theoretically expectated MHD stability properties of the corresponding configurations. A low l_i value is obtained to the fact we have chosen a flat current density profile in our equilibria analysis. As discussed later in the last section of this paper, out of the four presented equilibria, two of them (EQ#1 and EQ#2) are completely MHD unstable, one is fully stable (EQ#4) and the last one is partially stable (EQ#3). This describes (on purpose) a possible experimental situation where, with a stable profile it is possible to achieve the low q_{95} regime. Once there is the presence of small perturbation

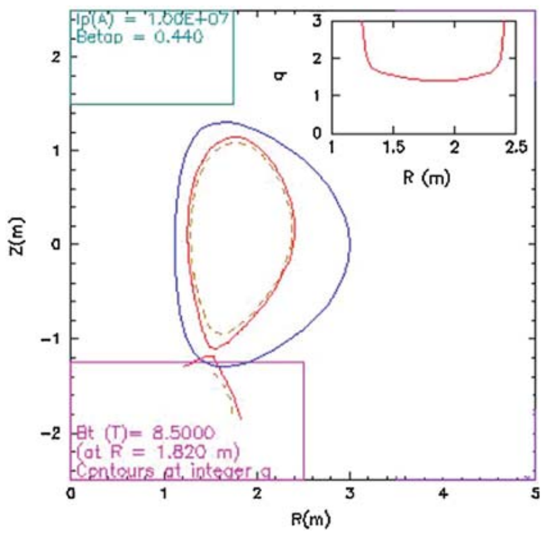

Fig. 2. Iso–$q(\psi)$ map; q_{95} and $q(\psi)$ = 2 surfaces are shown. The blue line is a simplified representation of the conducting structures. In the insert, the $q_\psi(R)$ profile is reported. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Table 1
Main plasma parameters of set of FAST equilibria at high plasma current and low q_{95} obtained by FIXFREE code.

Equilibrium	EQ#1	EQ#2	EQ#3	EQ#4
I_P (MA)	10	10	10	10
B_T (T)	8.5	8.5	8.5	8.5
β_p	0.44	0.44	0.44	0.44
l_i	0.48	0.50	0.60	0.66
q_{95}	2.54	2.30	2.27	2.20
q_0	1.38	1.37	1.12	1.03
b/a	1.98	1.87	1.79	1.78

it could drive the plasma towards the unstable profiles, but going throw the "window" of a partially stable configuration, where a feedback control can be applied, by a set of active coils, avoiding the occurrence of a hard disruption.

2.2. Transport analysis

In order to estimate the kinetic profiles (n_e, T_i, T_e) and confinement time that can be expected in the 10 MA/8.5 T FAST scenario, predictive transport simulations have been performed using the JETTO 1.5D transport solver [16] with one of the equilibria described earlier, but evolving the current density profile using neoclassical resistivity. The JETTO simulation reported here refers only to the heated flat-top phase. Its aim it to provide an estimate of the scenario performance in its full development, not to provide a study of the time evolution of the scenario since breakdown. The ramp-up phase including the breakdown is assumed similar to the scenario H-mode extreme (8 MA/8.5 T) discussed in [4,17] but has not been simulated for the specific 10 MA/8.5 T discussed in this paper. The GLF23 model [18] has been used to predict the n_e, T_i and T_e profiles as discussed in [17], but without taking into account plasma rotation, whose effects are expected small in this scenario. The steady-state profiles obtained are shown in Fig. 3. The heating applied was 30 MW of ICRH in (^{3}He)-D minority scheme, of which ~20 MW deposited collisionally to thermal ions and 7.5 MW to electrons, mostly collisionally. Z_{eff} was set to 1.5 and radiated power was 5 MW. In the present simulation the profiles are evolved from the given initial conditions at beginning of flat-top for a sufficiently long time (a couple of seconds) to reach steady simulations. During the run the q profile peaks and l_i increases up to 0.7. This is not in conflict with the equilibria

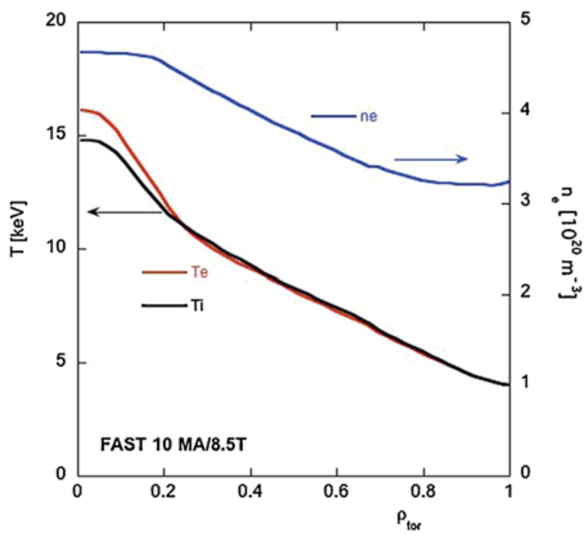

Fig. 3. Steady-state profiles of n_e, T_i, T_e simulated for the FAST 10 MA/8.5 T scenario using the GLF23 model in the JETTO transport code.

used in the MHD study, for which the most critical conditions have been analyzed. The L-H transition is not simulated, a pedestal is set as boundary condition since the beginning of the simulation. This is held fixed throughout the simulation. In any case to minimize GLF23 instabilities towards the edge a small Bohm term is added to the GLF23 turbulent transport, dominating over it outside ρ = 0.9. Pedestal values of n_e ($3.2\cdot10^{20}$ m^{-3}) and T_i, T_e (4 keV) have been chosen in order for the total confinement to follow the standard H-mode confinement scaling law, with $H_{98}\sim0.82$ taking into account the observation of confinement reduction in JET scenarios at low q_{95} [5–7]. The total energy confinement time was 0.5 s and the equivalent fusion gain Q_{DT} = 3.7. The Q_{DT} is calculated assuming 50/50 mixture of D and T, calculating the D and T density and temperature profiles according to GLF23 and with Z_{eff} = 1.5, and using SIMOD fusion model implemented in JETTO and described in [19,20].

3. Engineering constraints for high current – low q_{95} scenario

The time evolution of poloidal circuit currents that have been used to achieve one of the equilibria described earlier is reported in Fig. 4. During the strong β increase the plasma boundary is assumed to remain fixed since it foreseen to adopt a plasma control technique such as the eXtreme Shape Controller (XSC) used in JET including the Current Limit Avoidance system (CLA) [21]. The CLA has been recently designed and implemented to avoid current saturations in the PF coils when the XSC is used to control the plasma shape. The ramp-up phase has been assumed similar to the one calculated for the extreme H-mode FAST scenario discussed in [4,17]. However, as said before, following a suitable trajectory in the q_{95}-l_i plane during the plasma current ramp-up, it is possible to reach plasma equilibria at the very low $q_{95}\geq2$ [12]. The discharge at-top can last a couple of seconds (i.e. half the diffusive resistive time and twice the energy confinement time), and is limited by the heating of TFCs, as reported in [22]. On the contrary, the final temperature of PFCs at the end of the 10 MA/8.5 T scenario does not exceed the max temperature limit of 85 K [9], even if some of PFCs current density, as shown in Fig. 4, exceeds for few seconds the safe value (~32 MA m^{-2}) assumed for the reference scenario [4]. The evaluation of the end-of-pulse temperatures in the PFCs are shown in Fig. 5 and well discussed in [22]. In addition a preliminary ElectroMagnetic (EM) and structural analysis of the FAST PF system have been carried out in this high current scenario, well described in [22]. The resulting radial and axial forces are slightly more demanding than in the reference H-mode scenario and can be withstood without plastic strain occurring.

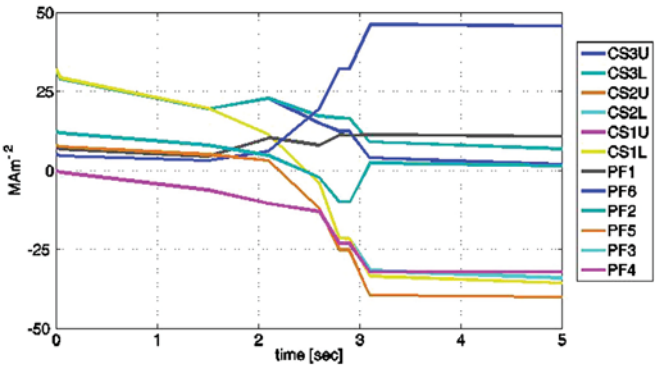

Fig. 4. PFCs current evolution for 10 MA/8.5 FAST scenario.

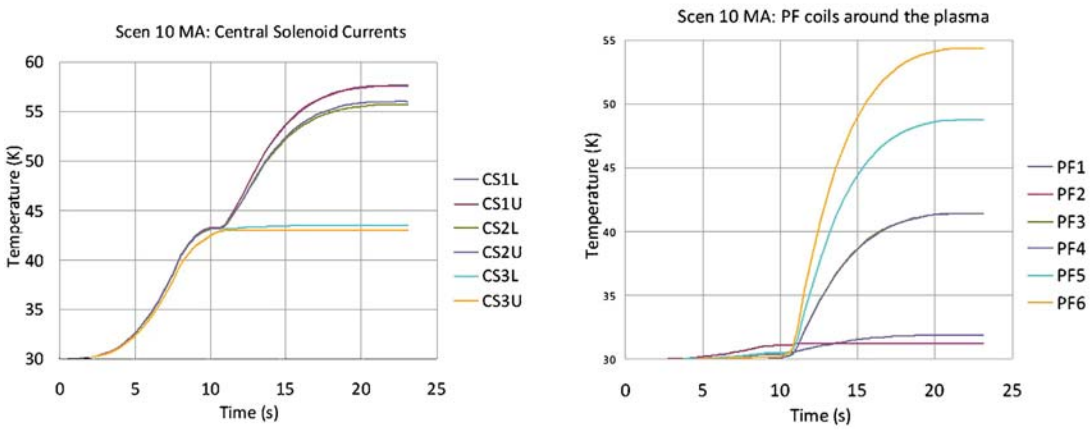

Fig. 5. Max poloidal coils temperature for 10 MA/8.5 FAST scenario.

In order to evaluate if this high current scenario is compatible with the current FAST design a Vertical Displacement Event (VDE) plasma disruption has been simulated and the maximum total vertical force applied on the Vacuum Vessel (VV) has been estimated. The operating scenarios of the VV are characterized by loads which are quite low during normal plasma behaviour and rather large during plasma disruptions. The worst disruption expected for the VV is a strongly vertically asymmetric VDE, capable to induce significant total vertical forces on the whole vessel. A VDE model where the vertical displacement of the plasma column is followed by a sudden loss of the plasma thermal energy (when the safety factor q goes below 1.5) and then by a fast current quench (1.5 MAm s^{-1}) is assumed. The values of the induced currents and loads have been calculated by using a proper axisymmetric finite element model with the MAXFEA MHD code [23]. The vertical loads induced during the 10 MA/8.5 FAST scenario are shown in Fig. 6. These preliminary results confirm that this high current scenario is compatible with the current FAST design. More details on this analysis are reported in [24].

4. MHD stability studies and feedback controlled active coils

With reference to the set of equilibria presented in Section 2, the capability of FAST passive conducting structures and active coils to stabilize and control potentially dangerous ideal and resistive MHD modes has been studied [8]. The stability analyses have been carried out with MARS [25], MARS-F [26] and CarMa [27] codes. Concerning the passive conducting structures, various different models have been considered, ranging from walls simply conformal to the plasma boundary, to more realistic description of the vacuum vessel and conducting plates (assumed as axisymmetric), as described in [8,28]. Ideal MHD current-driven modes have been studied, hence assuming the plasma as perfectly conducting. First of all, the ideal-wall limit position has been computed with the MARS and MARS-F codes. The results are summarized in Table 2 and briefly discussed here. More details are discussed in [8]. The equilibrium (EQ#1) was not suitable for our studies, since the conducting structures are too far, so that the instability will take

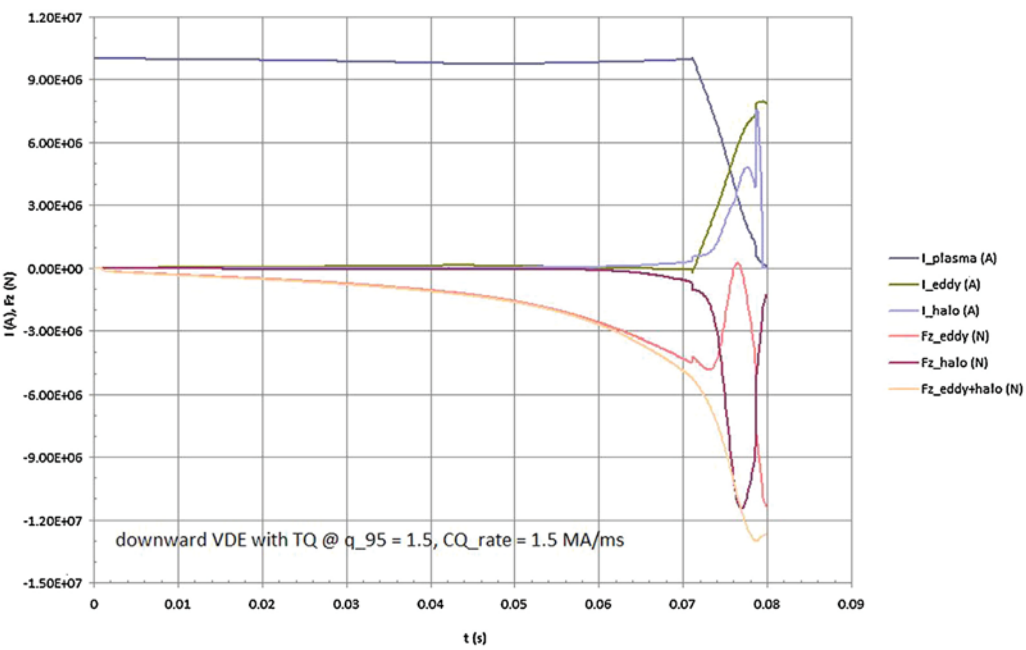

Fig. 6. VDE parameters and Fz EM force for FAST 10 MA/8.5 T scenario.

Table 2
Summary of MHD analysis for FAST high current – low q_{95} equilibria discussed in Section 2.

Equilibrium	EQ#1	EQ#2	EQ#3	EQ#4
$n=1$ (ideal mode)	Limit $b/a\sim1.3$	Limit $b/a\sim1.25$	Limit $b/a\sim1.4$	Stable
$n=2$ (ideal mode)	Limit $b/a\sim1.25$	Stable	Stable	Stable

place on Alfven times and hence will be probably almost impossible to actively control. For this equilibrium, the conducting structures intersect the ideal wall limit position. The same conclusions hold for the equilibrium (EQ#2). Conversely, equilibrium (EQ#4) is ideally stable, due to its favourable q profile – no ideal instability arises even with no wall. For the last equilibrium (EQ#3), the ideal mode shows the characteristics of a RWM: the $n=1$ ideal mode with realistic structures is unstable on electromagnetic times (with a growth rate time of few ms), so that its electromagnetic feedback control with active coils can be studied. To this purpose, some preliminary studies, presented in [8], suggest that FAST should be equipped with a set of feedback controlled active coils located between the first wall and the vacuum vessel and accessible for maintenance with the remote handling system, carrying currents up to 80 kA T with AC frequency up to few kHz [11].

5. Conclusions

The paper is a first attempt to describe the possibilities of achieving a low q_{95} scenario for FAST proposal. The main aim of this scenario is the preparation of a complete and reliable low q_{95} scenario aimed to develop some safe and robust tools to mitigate the occurrence of MHD driven disruptions, when operating close to some machine limit, under very large plasma magnetic and kinetic energy density conditions and with dimensionless physics parameters close to DEMO and ITER. To this purpose, FAST could be equipped with a set of feedback controlled active coils located between the first wall and the vacuum vessel and accessible for maintenance with the remote handling system, carrying currents up to 20 kA with AC frequency up to few kHz. The final target of a such MHD feedback loop is not necessarily the full stabilization of plasma operation at this very q_{95} low values, but at least the availability of a feedback control system able to mitigate the effects of potentially disruptive MHD activity, after detection of its onset. If successful, this would give the opportunity to change the operational point, so as to avoid the disruption and, possibly, even a controlled plasma shut down, in order to rebuild the plasma reference conditions, in a time as short as possible.

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