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Active toroidal field ripple compensation and MHD feedback control coils in FAST

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HIGHLIGHTS

- Active Ripple Compensating System (ARCS) consists of 18 off-centre poloidal coils between plasma and Toroidal Field Coils.
- The current in ARCS, adjustable and opposite to that in TFC, reduces the toroidal ripple below 0.2% at any toroidal fields.
- Feedback Active Control System (FACS) consists of two arrays of 9 in-vessel saddle coils fed by an MHD feedback controller.
- FACS allows robust feedback stabilization of low toroidal number MHD modes enabling plasma operations at low safety factor.
- ARCS and FACS are included in the whole FAST model and first engineering assessments show their feasibility and capability.

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ABSTRACT

The Fusion Advanced Study Torus (FAST) has been proposed as a high magnetic field, compact size tokamak providing a flexible integrated environment to study physics and technology issues in ITER and DEMO relevant conditions.

FAST has a quite large natural toroidal field ripple (around 1.5%) due to its compactness and to the number of access ports: this ripple must be lowered to an acceptable level to allow safe operations and a good confinement quality. An Active Ripple Compensating System (ARCS) has been designed, based on a set of poloidal coils placed between the plasma chamber and the Toroidal Field Coils (TFCs). These ARCS coils will be fed with adjustable currents, opposite in direction respect to the TFC currents, and will allow lowering the ripple up to zero and beyond.

The CAD model of FAST including the ARCS coils has been completed and preliminary electromagnetic and thermal analyses have been carried out.

Moreover, a Feedback Active Control System (FACS) composed of two arrays of in-vessel saddle coils has been designed to allow safe high plasma current, low safety factor operation and to mitigate possibly large ELMs effects in FAST. These FACS coils will be fed by a feedback system to control MHD modes: a first engineering assessment of the current requirements has been carried out.

1. Introduction

The Fusion Advanced Study Torus (FAST) proposal [1] for a high magnetic field, compact size tokamak machine has been designed as a very flexible tool able to investigate plasma wall interaction, to analyze power exhaust options and to study in an integrated way fast particles physics and steady state operation features in ITER and DEMO relevant conditions. To further increase the flexibility two additional systems have been added to the FAST design: an Active Ripple Compensating System (ARCS) dedicated to decrease the magnetic toroidal field ripple at any toroidal field value and a Feedback Active Control System (FACS) designed to control the potentially dangerous MHD modes allowing then low safety factor operation and possibly ELMs activity mitigation.

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2. Active ripple compensating system (ARCS)

The Toroidal Field Ripple (TFR) gives a measure of the toroidal magnetic field deviation from its nominal value all over the toroidal direction and can be evaluated [2] as

$$\mathrm{TFR}(r,z)=\frac{B_{\Phi,\max}(r,z)-B_{\Phi,\min}(r,z)}{B_{\Phi,\max}(r,z)+B_{\Phi,\min}(r,z)}$$

where $B_{\Phi,\max|\min}(r, z)$ is the max|min value of the toroidal field along the toroidal angle for a given point (r,z) in the poloidal plane. This variation, due to the finite number and toroidal extension of the Toroidal Field Coils (TFCs), is then especially relevant in compact tokamak with large port openings between TFCs, as in FAST where relatively large access ports have been foreseen for external heating, diagnostics and remote handling purposes. A large TFR should be avoided because it can produce significant losses of high energy particles, generate severe peaks in the heat loads on the First Wall (FW) and degrade the H-mode confinement quality. In FAST the plasma boundary is close to the Toroidal Field Coils and then the TFR is relatively high and reaches a maximum of about 1.5% along the separatrix on the equatorial plane for the reference H-mode scenario plasma shape, without any correcting system (Figs. 1 and 2, black lines, evaluated by Maxwell code). The insertion of ferrite plates between plasma and TFCs is the most straightforward and widely adopted system to reduce the TFR to acceptable values. Anyway, this solution has the drawback of being inaccurate [3] and unadjustable, leading then to an unavoidable overcompensation of the ripple when operating at a toroidal field lower than the design one. This is especially relevant in FAST, which has been designed to operate in a toroidal field range from 3.5 T (in steady state scenarios) to 8.5 T (in extreme performance scenarios).

In this work a different system to adjust the ripple amplitude has been evaluated by using Finite Element Models with the Maxwell EM code. This system is based on active poloidal coils placed between plasma and TFCs, fed with a current in the opposite direction respect to those in the TFCs [4]. A preliminary model of these coils has been drawn and integrated with the full CATIA5 CAD model of the FAST machine (Fig. 3): the coils are placed on the outboard between the plasma chamber Vacuum Vessel (VV) and the TFC and are composed by solid copper turns with a total conductor section of 400 mm (in the toroidal direction) × 100 mm (in the radial direction). The number of turns was chosen so that the current flowing in the ARCS was almost the same provided by the TFC power supply (89.2 kA at 7.5 T), avoiding then the need for a dedicated power supply. The electrical connection between ARCS and TFC circuit is implemented outside of the cryostat and then it will be possible in the future installing a dedicated power supply for the ARCS to carry out experiments at variable ripple values, for instance to study the ripple role in the pedestal behaviour, in the H-mode performance and in the fast particles confinement.

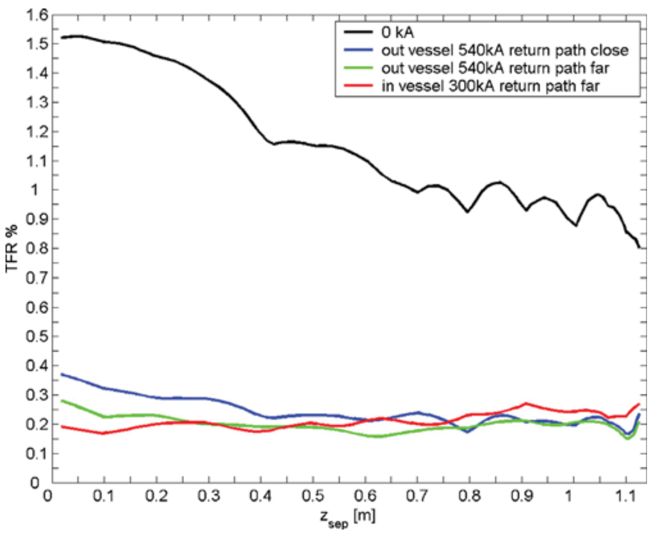

Fig. 1. TFR (%) along the plasma separatrix vertical coordinate $z(m)$, evaluated by Maxwell code: without correction (black); with 540 kAturn ARCS between VV and TFC by far return path (green); with 540 kAturn ARCS between VV and TFC by close return path (blue); with 300 kAturn ARCS between FW and VV by far return path (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

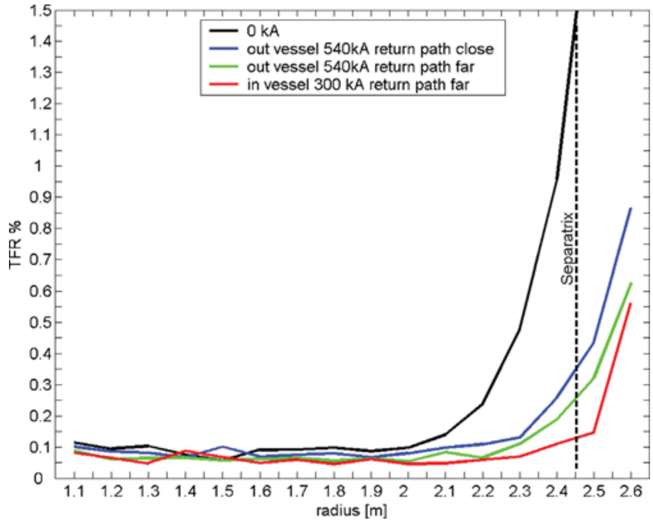

Fig. 2. TFR (%) on the equatorial plane $z=0$, evaluated by Maxwell code: without correction (black); with 540 kAturn ARCS between VV and TFC by far return path (green); with 540 kAturn ARCS between VV and TFC by close return path (blue); with 300 kAturn ARCS between FW and VV by far return path (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

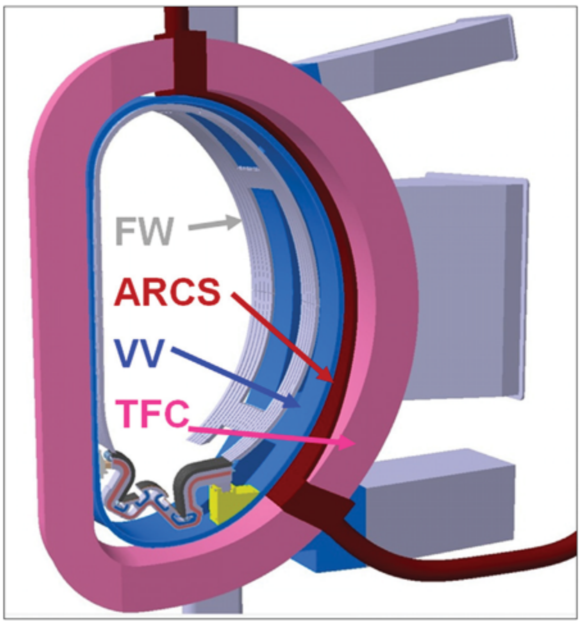

Fig. 3. CAD model of the FAST machine with the out-vessel ARCS coil (red) placed between the Vacuum Vessel (blue) and the TFC (pink). Also shown the First Wall (grey) and the divertor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

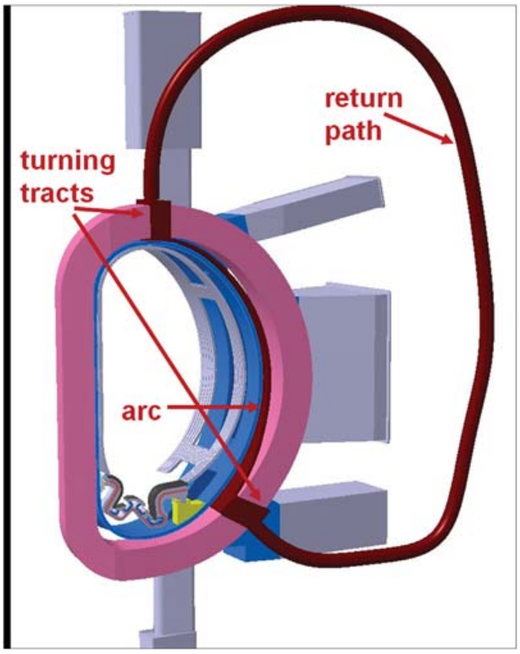

Fig. 4. CAD model of the FAST machine with the out-vessel ARCS coil with the return path (red) placed between the VV (blue) and the TFC (pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

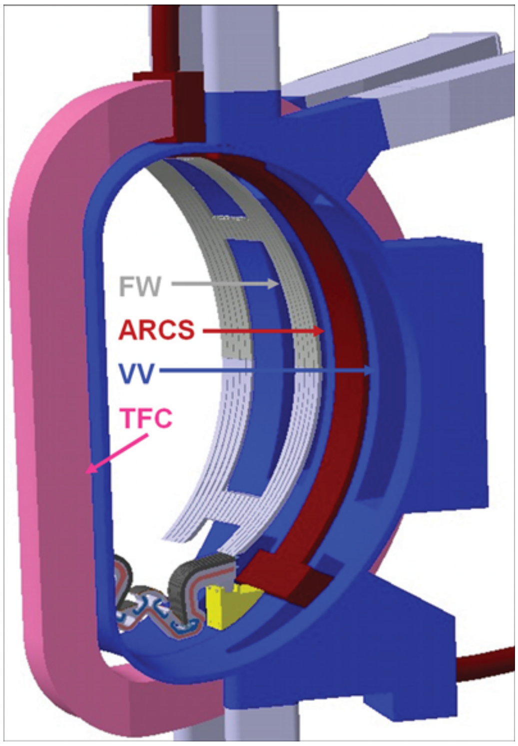

Fig. 5. CAD model of the FAST machine with the in-vessel ARCS coil (red) placed between the FW (grey) and the VV (blue). Also shown the TFC (pink) and the divertor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Moreover, a further improvement of the system, by the use of dedicated circuits for the active coils in chosen sectors, could allow a fine tuning of the ripple correcting the toroidal asymmetries produced by the ferromagnetic materials as those in the Neutral Beam shielding box.

The current required with this design to lower the ripple at a low enough level is 540 kAturn that is compatible with a six turns arrangement for the ARCS coils. The maximum TFR on the plasma separatrix with this current is around 0.2% (Figs. 1 and 2, green lines) and could be further reduced with a next refinement of the plasma shape, TFC bending and ARCS coils geometry.

The ARCS coils are composed by three main geometric parts: an arc placed between plasma and TFC, a tract turning around the TFC and a return path (Fig. 4) inside the cryostat but external to the TFC that provides also the connection to the power supply. The most suitable position, from an engineering point of view, for the return path is close to the TFC, but this option shows a significantly worst ripple reduction in the equatorial region (Figs. 1 and 2, blue lines), on equal current respect to the solution with the farthest return path. A detailed analysis of the manufacturing complexity related to both options will be undertaken simultaneously with the advances in the FAST load assembly design.

Another viable solution to reduce the current required by the ARCS consists in placing the arcs of the active coils inside the vessel and then closer to the plasma (Fig. 5). This design allows for a similar TFR reduction (Figs. 1 and 2, red lines) but with only 300 kAturn flowing in the active coils when using a return path as far as possible from the TFC. In this case, the constraint for the same current flowing in ARCS and TFC could be satisfied by a 3 turns design. On

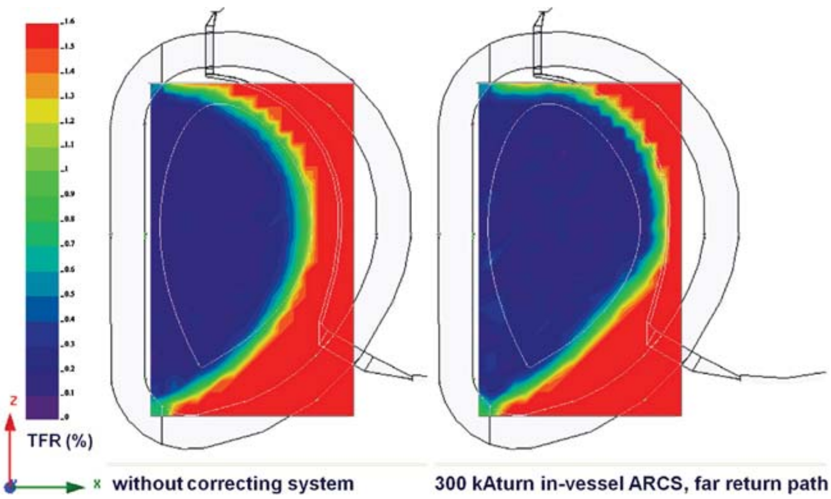

Fig. 6. TFR (%) on the poloidal section, evaluated by Maxwell code: without correction (left); with 300 kAturn in-vessel ARCS by far return path (right).

the other hand this solution could add a relevant complexity on the vessel design and on the remote handling issues, interfering with the locations of the FACS coils described in the next section, so a careful analysis should be performed.

The effect of the ARCS on a poloidal section, as for 300 kA in-vessel ARCS with far return path, is shown in Fig. 6. The area where TFR is below 0.2% appears noticeably increased and includes the whole plasma section. The shrinking of the intermediate TFR area (green in the colour map) reflects the higher multipole order of the ARCS correction respect to the field ripple. This figure shows also some numerical artefacts due to mesh size and the shortcoming of optimization in the downward section, where the ARCS geometry is only sketched at now.

The temperature increase for the ARCS coils were evaluated obtaining an upper value of 40 K for the coils placed inside vessel or 110 K for the coils placed outside the vessel when using the ARCS for the whole duration of the plasma pulse. A first evaluation of the Electro Magnetic (EM) forces in operating conditions (reference H-mode scenario at 7.5 T) on the arcs of each in-vessel active coil gives about 4.5 MN inward for the radial force and about 1.5 MN towards the equatorial plane for the vertical force on one half of the arc. The total radial torque respect to the plasma centre ($z = 0.1$ m) is evaluated below 0.2 MNm. These EM loads will require the careful design of a proper supporting system, especially if the arcs were placed inside the vacuum vessel. The stray field produced by the current in the active coils was also evaluated and never exceed 0.1 T near the plasma separatrix even in the worst case (arcs outside): its contribution to the total poloidal field (above 1 T in the same region for the reference scenario) and its perturbation of the plasma equilibrium is then negligible. This stray field, with the same toroidal periodicity of the TF coils, cannot produce islands in the plasma flux surfaces through resonant harmonics effect, while its non-resonant effects will be reduced as the overall TFR.

3. Feedback active control system (FACS)

One of the goals of FAST is contributing to the development of tools, techniques and scenarios relevant for the next ITER operational issues (plasma disruption prediction and avoidance, plasma control, giant Edge Localized Modes mitigation). In this context, the feasibility of a family of plasma scenarios near to the border of stability has been explored for FAST [5]. These scenarios are characterized by a very high plasma current, 10 MA at a toroidal field of 8.5 T, with a low safety factor q95 between 2.2 and 2.6. In these configurations, with a low safety factor at the edge and a q95 = 2 surface close the plasma boundary, both the kink and tearing MHD modes are unstable and can drive the occurrence of plasma disruptions. Recently, some experiments on RFX in tokamak configuration [6] showed the possibility of using active coils to control the resistive tearing mode associated with the q95 = 2 resonance when these coils are not far from the surface itself and then encouraged to extend these studies in FAST.

The safe and reliable operation in these conditions requires the development of robust tools to mitigate the occurrence of disruption driven by MHD activity, which could be very dangerous for the machine integrity [5] under operation close to machine limits with great plasma magnetic energy density. The FAST passive conducting structures together with a proper active coils system were proven to be able to stabilize potentially dangerous MHD modes [7] at low toroidal numbers; they will be also possibly used to mitigate the large ELMs (up to few MJ) produced by core MHD activity in H-mode scenarios with good transport quality and an ITER-like plasma edge. This design need has been satisfied by envisaging a Feedback Active Control System (FACS) made up of two arrays of 9 saddle coils located inside the plasma chamber between the equatorial and the oblique ports (Fig. 7). These saddle coils are equally spaced and extended all over the toroidal direction behind the FW (Fig. 8), around 25 cm far from the plasma edge. The coils are made up of four copper turns with a total section of about 100 mm × 100 mm and are designed to be remotely maintained, in case it was necessary. The one-turn self-inductance of such coils is around 3 μH; the one-turn mutual inductance with the closest coil is of the order of 0.05 μH. All other one-turn mutual inductances are below 0.01 μH.

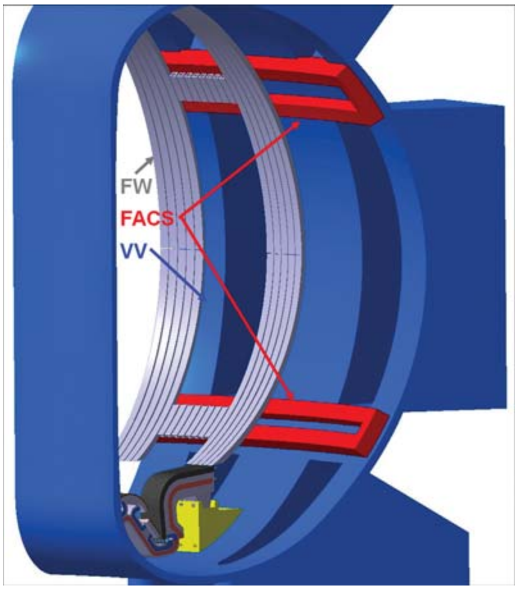

Fig. 7. CAD model of the FAST machine with the in-vessel FACS saddle coils (red) placed between the equatorial and oblique ports. Also shown the VV (blue) and the FW (grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

These FACS coils will be fed by a feedback system designed to control low toroidal number MHD modes allowing operation at high plasma current (up to 10 MA) and low safety factor.

A first engineering assessment of the design requirements shows that a suitable power supply and controllable phasing system, able to provide 20 kA with AC frequency up to few kHz can produce magnetic perturbation up to 1% of the poloidal field in the outboard region of the plasma separatrix. The maximum total current in each saddle coil with this design is then 80 kAturn, with a maximum current density of 8 MA/m2. The temperature increase due to this current has been estimated to be lower than 40 K. The Electro Magnetic (EM) forces produced on these coils during the reference scenario have been evaluated lower than 0.2 MN: a more

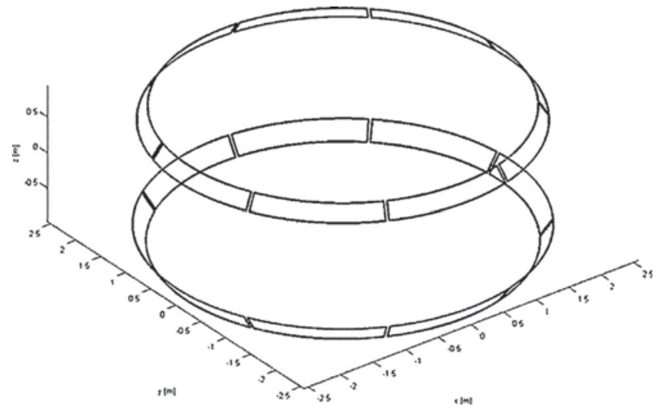

Fig. 8. Toroidal profile of the two arrays of 9 FACS saddle coils.

accurate evaluation of the EM forces during plasma disruption will be performed in a later phase. Both the temperature increase and the EM forces are fully compatible with the machine design.

To demonstrate the capability of the system to feedback control MHD unstable modes, the FACS coils have been modelled with a 3D finite elements mesh and included in a numerical model produced with the 3D CarMa code [8], in the perfect conductive wall limit. This control simulation has shown [7] the possibility of achieving a robust feedback stabilization of the ideal modes $n = 1$, $n = 2$ with a coil current slightly above 2 kAturn, well below the design limits. The stabilization of these modes could be then accomplished even with a reduced set of control coils, in case of a fault. It is also possible exploiting the residual control capability for an active mitigation of the resistive modes for safety purposes, as the avoidance of MHD-driven plasma disruption in operations close to the machine limits.

4. Conclusions

Two additional systems have been proposed to increase the flexibility of the FAST machine: one to actively reduce the toroidal field ripple and one to control dangerous MHD modes. These systems are made up of proper copper coils inside or outside the vacuum vessel, fed with current density such that the temperature increase and the EM forces during the plasma pulse were acceptable.

The Active Ripple Compensating System (ARCS) coils have been included in the CAD model of the whole FAST machine. Two options for these coils have been evaluated, in or out the vacuum vessel. The toroidal magnetic field ripple can be reduced with both these options below 0.2%: a next refinement of the plasma and coils poloidal profiles will be carried out to further reduce the maximum ripple in the whole plasma region and the current required to feed the coils. A first assessment of the related engineering issues shows that the system can be realized with a careful design.

The Feedback Active Control System (FACS) has been designed: it consists of two arrays of 9 saddle coils inside the vessel, equally spaced and extended all over the toroidal direction behind the FW. The proposed design can allow a robust feedback stabilization of the ideal $n = 1$, $n = 2$ toroidal MHD modes with currents well below the design limits of 80 kAturn with AC frequency of some kHz. A first assessment of the system shows its feasibility from an engineering point of view and the potential for MHD and resistive modes control. Further investigations will be performed to optimize the design and to fully characterize its modes control and disruption avoidance capabilities.

There is still much engineering work to do before the design for these subsystems could be completed but this way to increase the experimental flexibility of the machine seems to be very promising.

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