Fusion Engineering and Design xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Design of the new electromagnetic measurement system for RFX-mod upgrade

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ARTICLE INFO

Keywords:
RFP
Tokamak
RFX-mod
MHD mode analysis
Magnetic sensors

ABSTRACT

A major modification of the RFX-mod toroidal load assembly has been decided in order to improve passive MHD control and to minimize the braking torque on the plasma, thus extending the operational space in both RFP and Tokamak configurations. With the removal of the vacuum vessel, the support structure will be modified in order to obtain a new vacuum-tight chamber and the first wall tiles will be directly in front of the passive stabilizing shell inside of it, so increasing both the poloidal cross section and the plasma-shell proximity.

This implies the design of a new vacuum fit electromagnetic measurement system. The new local probes will be installed in vacuum onto the copper shell, behind the graphite tiles, and shall operate up to a maximum temperature of 180 °C to allow for baking cycles for first wall conditioning. Because of the reduced room available, tri-axial pickup probes have been designed, with the additional advantage of allowing the minimization of alignment errors.

The paper describes the detailed design of the new probe set, in particular highlighting advantages and effectiveness of different probe solutions. Preliminary tests carried out on local probe prototypes to characterize their electromagnetic behaviour are also reported.

1. Introduction

A major modification of the RFX-mod toroidal load assembly [1] consists in the removal of the vacuum vessel in order to increase both the poloidal cross section of the plasma (by 28 mm radially) and the plasma-shell proximity. This implies the modification of the support structure in order to obtain a new vacuum-tight chamber and the fastening of the new extruded graphite first wall tiles directly to the passive stabilizing shell inside of it.

The increased proximity of the higher conductive structure (copper shell with respect to Inconel vacuum vessel) is indeed expected to allow for spontaneous Tearing Modes rotation at higher plasma current [2,3] compared to RFX-mod, as well as to clamp the saturation amplitude of these modes at a lower value [3]. Moreover, thanks to the enlarged plasma cross section, a loop voltage reduction is also expected.

The whole magnetic measurement system needs to be redesigned. In particular, the new local probes (of size $42 \times 37 \times 7$ mm) will be installed in vacuum onto the internal surface of the copper shell, behind the graphite tiles, and shall operate up to a maximum temperature of 180 °C to allow for baking cycles for first wall conditioning. The spatial resolution is constrained by the number of graphite tiles, 28 in poloidal and 72 in toroidal direction respectively. Because of the reduced room available, three-axes pickup probes have been designed, with the additional advantage of allowing the minimization of alignment errors.

This paper presents a revision of the RFX-mod2 magnetic system layout and an update of the local field probe design reported in [4]. In Section 2 the requirements of the magnetic measurement system are described together with the constraints limiting the design choices. The outcoming considerations from an assessment of the effect of the position error of local measurement probes and the comparison with the adoption of wider saddle sensor are given in Section 3, highlighting the benefits of the two solutions. In Section 4, the definitive magnetic measurement set is reported, together with a detailed description of the local magnetic field measurement probe design and results of preliminary tests carried out on some prototypes. Some conclusions are drawn in Section 5.

2. Constraints and requirements

The system of magnetic probes, integrated with an extended set of

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https://doi.org/10.1016/j.fusengdes.2019.01.110
Received 8 October 2018; Received in revised form 18 December 2018; Accepted 22 January 2019
0920-3796/

electrostatic and calorimetric probes, is devoted to the study of both global plasma parameters and low frequency MHD phenomena, which largely affect the plasma equilibrium. The successful results in terms of MHD control experiments in RFP discharges [5], as well as of low-q circular [6] and shaped Tokamak experiments, entails a system of probes with high sampling capability along both the toroidal and poloidal direction.

On the other hand, the twofold aim of using the same system for both equilibrium and shape control, and for MHD active control and physics analyses, makes the requirements particularly stringent in terms of reliability and redundancy on one side, and of precision on the other.

Therefore, the design of the in-vessel measurement system is a compromise between the above requirements and the resulting complexity and cost. The presence of the tiles introduces a basic constraint on the spatial resolution and dimension of the local probes, while the available number and size of ports set a limit for the number of measurement signals.

2.1. Equilibrium and shape control system

Tokamak Single and Double-Null discharges were carried out in RFX-mod with an active plasma shape control system designed on the basis of the standard approach of controlling a certain number of distances (gaps) between the plasma boundary and the first-wall, measured along radial directions [7]. Before the upgrade, RFX-mod was equipped with eight evenly spaced flux loops and 6 "dense" poloidal arrays each consisting of 8 evenly spaced biaxial pickup sensors (poloidal and toroidal components) providing the poloidal field measurement required for the plasma boundary reconstruction. However, the previous system did not allow the direct calculation of the 4th, 5th and 6th poloidal harmonic which contribution was proved to be not negligible. Moreover, even the calculation of lower harmonics is affected by errors due to the aliasing of higher harmonics produced by the 16 Field Shaping (FS) coils, the plasma and eddy currents, which calls for the direct measurement of a greater number of harmonic coefficients in order to achieve a plasma boundary reconstruction with adequate precision. Taking into account the constraint of 28 tiles per poloidal array inside the copper shell, the minimum requirement for a completely measurement-based and reliable equilibrium reconstruction is 14 sensors per each array for the measurement of the poloidal and radial component. The number of "dense" poloidal arrays is increased to 12 in order to be more flexible, depending on the expected non-axisymmetric behavior of the plasma equilibrium.

The proposed number of 12 is due to requirements of the toroidal field configuration analysis in RFP and Tokamak discharges, as explained later.

As the poloidal flux probes need to be placed outside the shell for better protection from plasma (the same holds also for the installation of saddle probes larger than the first wall tiles), a direct measurement of the local radial magnetic field component is deemed useful. For this reason the adoption of tri-axial probes appears the most advisable, also because it allows for a precise compensation of misalignments introduced during the assembly of the system. The high number of sensors in the poloidal arrays will also allow to get rid of the Rogowski coils for the measurement of the plasma current, by calculating it with good approximation as linear combination of the poloidal field measurements.

An accurate measurement of the toroidal field component and the toroidal flux is required for the RFP studies. In addition to the local tri-axial magnetic field measurement, the system will be integrated with 12 toroidal flux loops, one for each of the toroidal field coil sectors, which are fed by independent power supplies. This high toroidal spatial resolution should allow a more precise measurement of the small diamagnetic component in Tokamak discharges, particularly prone to noise.

Since the system time response is imposed by the FS coils and their power-supplies, which are actually the same as in RFX-mod, no additional dynamic requirements for the measurement chain are foreseen for the new shape control system (0–500 Hz frequency range). On the other hand, any substantial variation of the vertical instability growth rate (now beyond 100 ms according to a plasma response model in SN configurations) is expected and it could be possibly reduced by the increased proximity of the plasma with the highly conducting copper shell.

2.2. MHD active control and physics analysis

In order to correctly identify the high n ($n \geq 6$) MHD mode spectrum expected in RFP discharges, with a poloidal periodicity at least of $m = 2$ (because of the toroidal coupling and getting rid of the $n > 24$ aliased mode), it was exploited the full toroidal periodicity of the tiles designing a set of 6 (poloidal) × 72 (toroidal) pickup sensors. In this case, the alignment compensation possibly provided by the tri-axial sensor would be particularly important, since the B_ϕ component is the lowest one and a small tilt of the probe would cause a pickup from the B_θ component. However, due to the limited number of available feedthroughs, which must be shared with the electrostatic and thermo-mechanical measurement systems, it was decided to adopt mono-axial pickup coils for the detailed measurement of the toroidal MHD spectrum. A cross calibration is foreseen in the commissioning phase for the equilibrium and shape measurement system by means of ad hoc dry shots in order to compensate for possible misalignment.

The knowledge of the B_r map is assured by the tri-axial sensors as well, but an additional set of 4 (poloidal) × 72 (toroidal) saddle probes will be mounted.

3. Considerations on the magnetic measurement set choice

In the following subsections, criteria for the optimal choice of the magnetic sensors for RFX-mod2 are described. As a matter of fact, the first proposal of sensor allocation reported in [4] had to be modified because of the limited number of vacuum feedthrough available. The objective is to maintain a high spatial resolution, accepting to give up some redundancies initially proposed.

3.1. Local and saddle probes comparison with respect to positioning error

Since in RFX-mod2 the new local probes will be integrated within the thin copper shell, they can be subject to larger and additional positioning errors with respect to RFX-mod, where mainly the rotation around the radial direction (θ, ϕ toroidal surface) could affect the measurement.

In particular, they can experience a misalignment in toroidal (r, ϕ) and in poloidal direction (r, θ) due to a deformation of the shell. In the former case, supposing a deformation of 1 mm in radial direction from the torus, the measured radial field would include 1% of the toroidal field. While in RFP configuration this is not an issue, in Tokamak operation (where the toroidal field will be of the order of 0.5 T) the crosstalk would be about 0.5 mT. This is not the case for saddle sensors spanning an angle of $\pi/4$ poloidally (completely covering the toroidal surface), for which the pick-up results more than halved. Similarly, in the case of the latter deformation, the fraction of poloidal field wrongly measured as radial field would be equal to the ratio between the radial position error and the poloidal dimension of the sensor. In other words, the smaller the poloidal extension of the probe, the higher positioning precision is required. For example, considering again a position deviation of 1 mm, a saddle coil spanning $\pi/4$ along the poloidal direction would detect a poloidal field pick-up of 0.25%, which corresponds to 2 mT given a poloidal field of 0.8 T. In order not to exceed a similar pick-up with a local probe (with poloidal dimension of 4 cm), the misalignment error must be lower than 0.1 mm.

3.2. Local and saddle probes comparison with respect to radial field harmonic reconstruction

Neglecting the pick-up effect, the evaluation of the effectiveness of

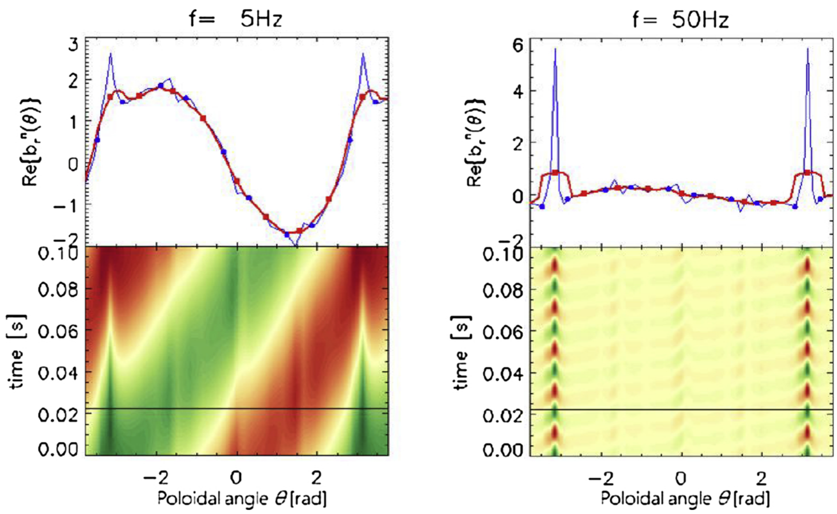

Fig. 1. Poloidal dependence of the real part of a simulated $n = 7$ radial component measured with virtual local (blue) and saddle (red) probes, for two frequency (5 Hz left and 50 Hz right). On the bottom time evolution of the perturbation measured with the local probes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the two solutions on the correct radial field spatial harmonic determination is useful in assessing the best magnetic probe system.

Since the saddle coils measure a radial field value that is integrated on a sector of toroidal surface, the derived toroidal harmonic corresponds to the averaged measurement of many local probes spanning the same poloidal angle θ. The Fourier representation of the averaged function is more attenuated the higher the poloidal harmonic m is.

In RFP configuration, where low m harmonics are of interest, this is an advantage, since the lower sensibility to high spatial frequency results in an attenuation of the unavoidably aliased harmonic (see Fig. 1). In particular, in RFX-mod high order poloidal harmonics are introduced by the presence of the toroidal gap on the conductive shell. Saddle probes are therefore considered more reliable with respect to pick-up rejection and signal reconstruction.

3.3. On the use of B_θ measurement

In tokamak configuration, where the MHD modes have particularly low amplitude, the crosstalk of the toroidal field component on the B_θ measurements of RFX-mod was significant, but easily compensated exploiting the measurement of the biaxial probes in dedicated dry shots with toroidal field only. In RFP configuration, the amplitude of the B_θ and B_ϕ component is inverted and in this case the crosstalk of the poloidal field on the B_ϕ measurements is observed.

However, in this case the cause of the crosstalk is not limited to the rotation of the sensors on the plane tangential to the torus, rather it includes the pick-up at the vacuum-air feedthroughs and other uncontrolled interferences along the signal path. In other words, the correction using the B_θ measurement is of limited utility.

4. Magnetic diagnostic set final design

Taking into account the above mentioned requirements and constraints, the final set shall consist of 1216 magnetic probes of different typologies as summarized in Table 1. A graphical representation of the proposed layout of pick-up and saddle probes, together with the available ports for signal feedthrough, is shown in Fig. 2.

Table 1
Types and layout of magnetic probes.

Type of probe	Measurement	Layout
Three axes pick up	Local magnetic field (B_θ, B_ϕ, B_r) + Plasma current	12 equispaced shifted poloidal arrays of 14 probes
One axis pick up	Local toroidal field (B_ϕ)	6 uniform toroidal arrays of 72 probes
Saddle loop	Averaged radial feld (B_r)	4 along poloidal and 72 along toroidal direction fully coveraging the torus
Single toroidal loop	Poloidal vloop + Poloidal flux	8 + 8 equispaced
Single poloidal loop	Toroidal vloop	12 equispaced

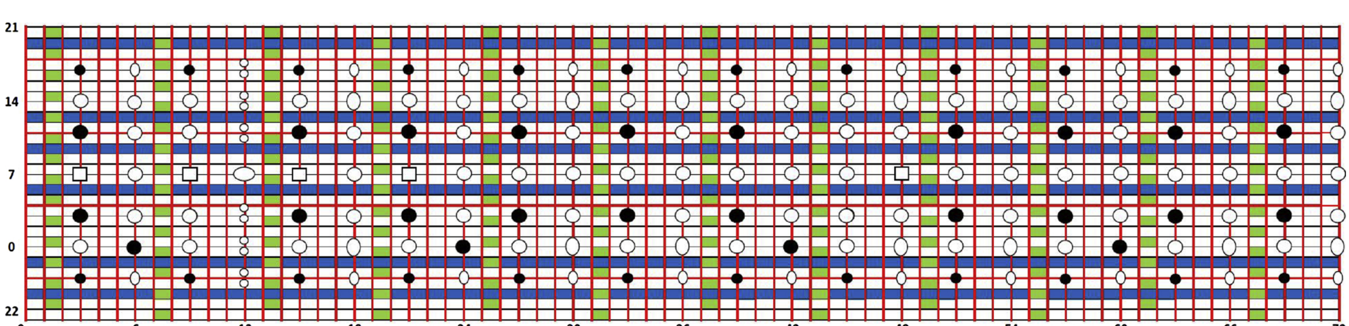

Fig. 2. 2D projection of RFX-mod2 local and saddle probe layout. Three axes probe in green, one axis in blue, saddle probe in red. Black circles represent the available ports for in-vessel measurements feedthrough (magnetic, electrostatic and thermo-mechanical). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

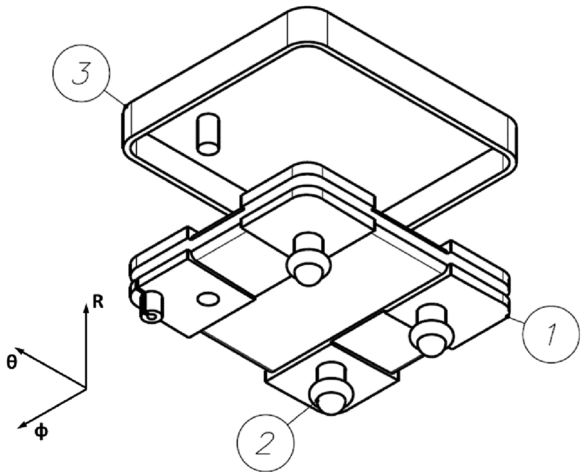

Fig. 3. Isometric view of tri-axial pick up probe showing the winding reel (1), the fixing rivets (2) and the cover (3).

4.1. *Three axes pick up coil design*

The use of three axes probes for local measurement of radial, poloidal and toroidal magnetic field components allows an installation time reduction with respect to separate probes, as well as the possibility of correcting misalignment errors as already discussed.

Three independent orthogonal windings of enamelled copper wire are wound on a Torlon® core, shown in Fig. 3. It consists of the reel where the wires are wound and a cover with protective function and to maintain the windings fixed in position without the use of any adhesive tape, not allowed in vacuum environment.

The reel is fastened behind the graphite tiles directly on the copper shell by three copper rivets. The side facing the shell is carefully machined to fit the poloidal curvature in order to minimize the radial size and position misalignments. A fourth drilled pin is foreseen for guiding the three twisted copper pairs from the windings out of the toroidal shell through a dedicated 5 mm diameter hole.

The 0.14 mm diameter wire of the winding is connected to a thicker 0.25 mm one for the connection out of the vacuum chamber, Wires junction is devised in order to keep each pair well twisted and thus minimizing the picked up signal.

The choice of Torlon® as core material is motivated by its high thermal stability and thermal expansion coefficient very close to the copper one [8]; the shape is optimized to keep the winding well tight to the core and thus minimizing effective area variations during the probe lifetime due to thermal cycles.

Probe characteristics are summarized in Table 2.

Preliminary tests have been carried out by two external companies on some prototypes on PEEK cores, in order to assess the feasibility of the windings. These tests include dimensional verifications, measurement of the electrical parameters, of the effective area of each winding and of their orthogonality by measuring the relative pick-up. In Fig. 4 a representative sample which passed the tests is shown.

Table 2
Three axes pick up probe typical characteristics.

Dimensions	44 × 39 × 7 mm
Core material	Torlon® 5530 PAI
Wire type	Class 200 grade THEIC polyesterimide enamelled copper wire
Wire diameter	0.14 mm (copper)
Nominal turn n°	240 (B_r), 190 (B_θ), 132 (B_ϕ)
Magnetic section	0.25 m^2 (B_r), 0.03 m^2 (B_θ), 0.028 m^2 (B_ϕ)
Resistance	36 Ω (B_r), 18 Ω (B_θ), 15 Ω (B_ϕ)
Coils orthogonality	± 0.5%

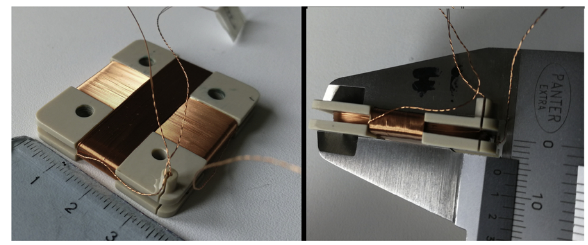

Fig. 4. Photo of a prototype of three-axes pick up probe (without cover).

5. Conclusions

The magnetic diagnostic set for the upgrade of the RFX-mod machine was completely redesigned in order to satisfy the requirements under stringent constrains, at the same time improving the harmonic reconstruction capability and in turn allowing the possibility of exploring the whole operational space in both RFP and tokamak configuration.

The overall layout was revised in order to minimize the probe number and to take into account the actual effectiveness of the use of three axial local probes for the different measurement needs.

The present design is now in the conclusive development phase, the whole machine is expected to be assembled in late 2019 and the first plasma in 2020.

Acknowledgements

The modification of RFX-mod is co-funded in the framework of the industrial innovation project MIAIVO, granted by Regione Veneto POR-FESR 2014-2020 (Regional Operational Program for the European Regional Development Fund).

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