Fusion Engineering and Design 130 (2018) 94–103

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Numerical assessment of geometrical and magnetic parameters for dummy double pancake of ITER PF1 coil using optic and magnetic measurements☆

V. Amoskov[a,*], V. Belyakov[a,b], M. Burkanov[c], A. Bursikov[a], A. Firsov[a], Yu. Ilyin[d], V. Kukhtin[a], E. Lamzin[a], M. Larionov[a], B. Lim[d], A. Mednikov[a], A. Nezhentzev[a], I. Rodin[a], N. Shatil[a], D. Stepanov[a], S. Sytchevsky[a,b], A. Ustinov[e], V. Vadatursky[c], V. Vasiliev[a]

[a] *JSC "D. V. Efremov Institute of Electrophysical Apparatus", 3 Doroga na Metallostroy, St. Petersburg, 196641, Russian Federation*
[b] *St. Petersburg State University, 7/9 Universitetskaya embankment, St. Petersburg, 199034, Russian Federation*
[c] *JSC "Sredne-Nevsky Shipyard", 10 Zavodskaya st., 196643, St. Petersburg, Russian Federation*
[d] *ITER IO, Route de Vinon-sur-Verdon, CS 90 046, 13067, St. Paul Lez Durance Cedex, France*
[e] *Institution "Project Center ITER", Building 3, Kurchatov sq. 1, 123182, Moscow, Russian Federation*

ARTICLE INFO

Keywords:
ITER
PF coil
Magnetostatics
Current centerline
Inverse problems
Shape deformation
Error fields

ABSTRACT

A measurement-based numerical reconstruction technique is proposed to control winding geometry of the poloidal coils manufactured for ITER. A detailed coil model is parameterized in terms of the magnetic characteristics. Deviations from the specified coil shape are evaluated in a comparison of reconstructed "ideal" field and data of magnetic measurements. The technique has been validated in the course of quality inspection of the dummy double pancake similar to the pancakes of the ITER PF1 coil. Experimental results are presented.

1. Introduction

In tokamaks, including ITER [1], perturbations of axial symmetry of the poloidal field, or error fields, can induce locked modes in stable plasma [1,2]. The main source of field perturbations are unavoidable shape distortions occurred during fabrication and assembly of coils. Field perturbations above the limit, called Locked Mode Threshold, result in plasma instability and cause plasma disruptions.

Theoretical and experimental investigations carried out on existing tokamaks [2–8] have contributed to the error field issues and the underlying physics. In the ITER machine [9], severe limitations are adopted on the allowable level of field non-axisymmetry and, therefore, geometrical tolerances for the coils [10,11]. Thus, the coil dimensional inspection is essential for manufacturing process of the ITER magnets [12–19].

JSC "NIIEFA" (Russian Federation) is responsible for the fabrication of the ITER PF1 coil. In the course of PF1 manufacturing preparation a quality control technique has been proposed on the basis of several dedicated studies [12–14] to provide an assessment of coil geometry using optical and magnetic surveys combined with numerical simulations. A special computational algorithm was developed to reconstruct distortions of the coil geometry by means of comparing the measured coil field and simulated "ideal" coil field map.

The results reported in [12] demonstrated a feasibility of numerical reconstruction of coil misalignments and deformations using the data of magnetic measurements. The technique was experimentally validated in reconstruction of displacements and tilts of a test round coil from measured magnetic parameters [13]. Then PF1 scaled dummies were manufactured and the prototype measuring system was designed and built [14]. A series of magnetic measurements were performed with these dummies and prototype. A comparison of experimental and simulated results demonstrated the reliability of proposed dimensional inspection technique.

Dummy Double Pancake (DDP) is used to qualify PF1 tooling and manufacturing processes before the start of actual production. Full-scale PF1 DDP is similar to real pancakes in every aspect except one: the cable is made of copper wires instead of NbTi superconducting strands [20]. This paper presents results of the PF1 DDP dimensional inspection, which was performed as a numerical reconstruction of DDP geometrical parameters from the data of magnetic measurements.

The reported study was aimed to:

☆ ITER is a Nuclear Facility INB-174. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

* Corresponding author.
E-mail address: amoskovvm@yandex.ru (V. Amoskov).

https://doi.org/10.1016/j.fusengdes.2018.02.076
Received 11 August 2017; Received in revised form 31 January 2018; Accepted 20 February 2018
Available online 29 March 2018

- test and optimize geometrical and magnetic measurement procedures;
- recommend possible improvements for the measuring procedures;
- assess geometrical and magnetic parameters of the fabricated DDP;
- compare results of the inspections with the adopted tolerances.

The measurements were performed on the PF1 assembly shop, which is a part of the PF1 manufacturing building located on the territory of the Sredne-Nevsky Shipyard, St. Petersburg. DDP field simulation requires an accurate description of the ferromagnetic surroundings, that is why a PF1 manufacturing and inspection plan (MIP) requires preventing uncontrolled movement of ferromagnetic structures for the PF1 assembly.

2. PF1 dimension tolerances

Conventional dimensional inspection techniques, based on geometrical measurements, cannot check the position of the turns and layers inside the winding pack, as direct geometrical measurements there are impossible. For this reason, two sets of tolerances are adopted for the PF1 manufacture and assembly [1]:

1) deviations of the current centerline (CCL) that could lead to a shift of the coil magnetic centre, tilts of the magnetic axis, etc.
2) deviations of the overall dimensions and turn shape deformations.

The PF coils manufacturing process used by IO [1,9] implies mandatory constraints on typical geometrical distortions of the coils (see Fig. 1). The tolerances specified for PF1 are listed in Table 1. Tilts are clearly associated with the coil manufacture (γ_z) or installation/assembly (δ_z) processes. However, it is hard to attribute the shifts δ_x and δ_y in a similar way. Further on, both of them are treated as of the manufacturing origin. The same tolerances δ_x, δ_y, γ_z can be applied to a separate DP.

Table 1
Manufacture and assembly tolerances for ITER PF1 related to CCL [9].

Deviation	Designation	Tolerance
Horizontal shift along axis *X* or *Y*	δ_x, δ_y	± 2 mm
Ellipticity	γ_x, γ_y	± 3 mm
Warping	γ_z	± 1 mm

3. Measurement-based computational algorithm to validate coil geometry

According to [12–14], a coil geometry is inspected by means of optic and magnetic measurements. To measure magnetic parameters, a coil and a measuring unit should be moved relative to one another. We consider a measuring system with stationary sensors and a movable coil. The coil is placed at *K* reference positions where its magnetic characteristics are recorded. Such configuration is dictated by the presence of massive steel structures on the assembly site.

As a result, we can specify fixed positions of sensors and ferromagnetic surroundings in a global right-handed Cartesian coordinate system OXYZ.

3.1. Coil positioning from optic measurements

The movable coil has *M* gauge marks on its internal circumference. Angular coordinates of these marks can be measured with a theodolite and their linear coordinates with a laser ranger or similar instrument.

We assume that the coil can be modelled in the approximation of a perfectly rigid body. Then, coil deformation is expected to be negligibly small at motion. The coil position is described with 6 basic parameters of the coil geometrical center related to the origin of the global coordinate system:

Three linear components define the shift vector

$$\mathbf{S} = (s_x, s_y, s_z)^T \tag{3.1}$$

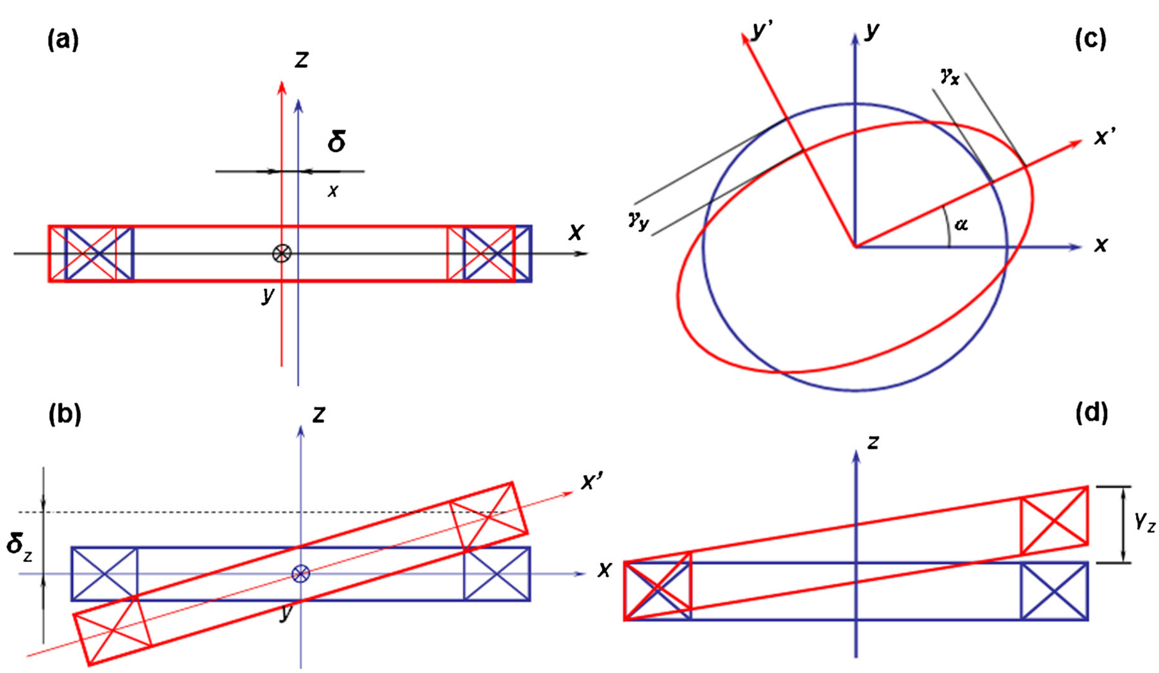

Fig. 1. Basic deviations of shape and position specified for ITER PF coils [1,9] (a) horizontal shifts δ_x and δ_y of coil magnetic center with respect to geometrical center; (b) tilt δ_z of coil magnetic axis; (c) ellipticity, that is deformation of the coil shape in plane XY determined by sizes γ_x and γ_y of elliptic semiaxes and rotation α in plane XY. (d) warping, determined by vertical shift γ_z and horizontal angle α_z of CCL, treated in practice as coil tilt [10] (Fig. 1b).