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ORIGINAL RESEARCH

Numerical analysis of ITER fourth poloidal field (PF) coil feeder

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Abstract The ITER poloidal field (PF) feeder busbar which carries 52 kA current will be subjected to high Lorentz force due to the background magnetic field aroused by the coils and the self-field between a pair of PF busbars. Peak magnetic force requires dense supports. But to minimize the heat load to the busbars as well as the cryo-pipes, fewer and thinner supports design is proposed, so a balance between mechanical strength and thermal insulation performance should be achieved. This paper presents the analysis on support system design for ITER 4th PF feeder including the S-bend box, the cryostat feed-through, the in-cryostat-feeder. An electric–magnetic coupled analysis aims to get real magnetic force load under the worst scenario, then the Lorentz force result is imported into the mechanical analysis, applied on the busbars, meanwhile the busbar supports, the containment duct, the gimbals, the separator plate and the cryo-pipes, the cold mass supports are contained in the finite element model to check the full system performance under Lorentz forces, earth gravity and thermal contract at 4.5 K. Based on the analytical results, the quantity and the spaces between busbar supports in the 4th PF feeder have been studied and the detail design optimized.

Keywords ITER · 4th PF feeder · Supports · Lorentz force · Mechanical analysis

Introduction

The ITER feeder systems, consists of 31 units, connect the ITER magnet systems located inside the main cryostat to the cryo-plant, power-supply and control system interfaces outside the cryostat. The feeders are the supply-lines to the ITER magnet systems. The main purpose of the feeders is to convey the cryogenic supply and electrical power to the coils as well as house the instrumentation wiring. The feeder carries superconducting busbars, supercritical cryo-pipes and instrumental pipes, which working in vacuum and 4.5 K, from the coil terminal box (CTB) to the coil. The poloidal field (PF) busbar which carries 52 kA current will be subjected to high Lorentz force due to the background magnetic field aroused by the toroidal field (TF) coils, PF coils, central solenoid (CS) coils, correction coils (CC) and the self-field between every pair of PF busbars. Peak magnetic force could be 6 t/m in the ICF region that requires dense supports. But to minimize the heat load from 80 K thermal shield to the 4.2 K busbars as well as the cryo-pipes, fewer and thinner supports design is proposed, so a balance between mechanical strength and the quantity and structure of supports should be achieved, and several numerical analysis are performed to check the performance on design concepts in this paper [1, 2].

Design structure for PF4 feeder

Figure 1 shows the configuration of PF4, and the following introduction lists the main components comprised in the feeder assemblies, from out-board to in-board, and briefly summarizes their main functionalities.

The CTB houses the cold to warm transitions of the High Temperature System (HTS) current leads and the cryo-

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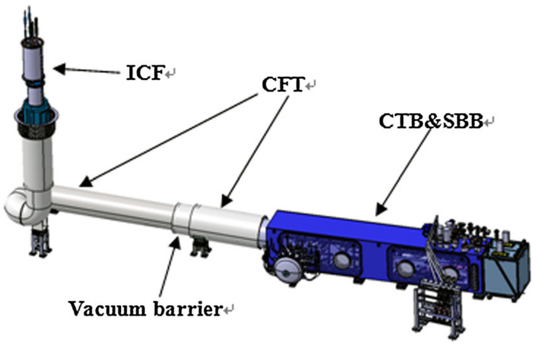


Fig. 1 Typical structure of PF4 feeder

control valves for regulating the liquid helium supply to the coils and feeder busbars. The S-bend box (SBB) contains S-shaped bends in the busbars and the cryo-pipes. The CTB and SBB form a single mechanical unit (combined box) because there is no busbar joint between them. And the integrated length of them (exclude dry-box) is 7.8 m long with an overall weight about 25 t. An 80 K internal thermal radiation shield covers all inner surfaces of the CTB and SBB to keep 4.5 K in working. Most of the feeder instrumentation is located in the CTB. The S-bends accommodate the differential thermal contraction between the cryogenic feeder components at 4.5 K and at room temperature. The CTB and SBB vacuum system is in common with the cryo-distribution line, which is separated from the Tokamak cryostat vacuum with a vacuum barrier located between the SBB and the cryostat feed-through (CFT).

The CFT is two straight parts with the intermediate space U-bend of the feeder system (See Fig. 1), which connects the SBB with the in-cryostat component of the feeder (ICF). The CFT is bounded by the in-cryostat and the intermediate joints. It passes through the bio-shield and welded to the cryostat. The CFT assembly consists of the busbars, the cryo-pipes, the instrumentation pipes, the internal supports (busbar supports and pipe supports), the separator plate, the containment duct, the cold mass supports, the thermal shield, the vacuum barrier, the cryostat extension duct, and the gravity supports. The CFT shares the vacuum with the main cryostat, separates from SBB by the vacuum barrier. It is cooled by its thermal radiation shield with 80 K helium.

The main in-cryostat component of the feeder (ICF) components include the containment duct and the internal supports, cooling pipes and instrumentation pipes layout, busbars, separator plate and the interfaces to the coil terminal and feeder CFT section [1–3].

Basic analysis model for PF4

There are total 6 PF feeders at Tokamak system, although carrying same current, each of them has different routing, different location and different designed structure, so will suffer different magnetic field and Lorentz force. This analysis aims to get the suitable PF4 busbar support system and check PF4 full system performance. Firstly to get real magnetic force load under the worst scenario, an electric magnetic coupled analysis which includes the PF4 busbars and the coils is performed, then the magnetic analysis result is imported into the mechanical analysis, applied on the busbars, meanwhile the obtained busbar supports and other critical components are contained in the model to check the full system performance under Lorentz forces, earth gravity and thermal contract at 4.5 K [4–6].

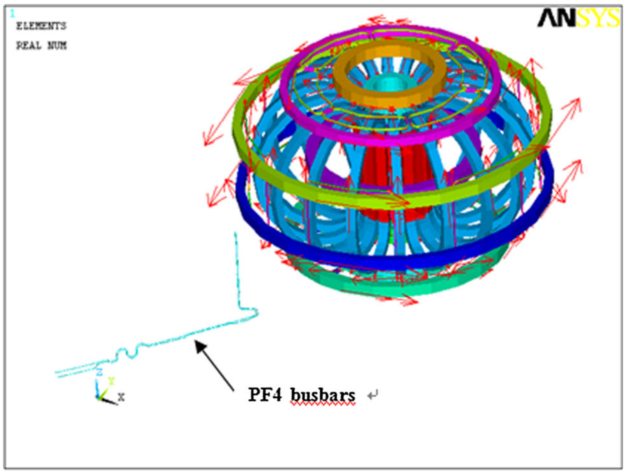


Fig. 2 Magnetic model (including coils and PF4 busbars)

Magnetic analysis model for PF4

This analysis aims at the magnetic field and Lorentz force on the PF4 busbars in the worst scenario which is defined in the feeder magnetic analysis (ITER_D_2F7R6 K v0.3), in this scenario, all coils are charged with peak working current, while the plasma current is zero (quenching), so the feeder busbars will sustain the worst electromagnetic force [1, 2].

The magnetic model contains the all coils (including the 18 TFs, 6 PFs, 6 CSs and CC coils) and a pair of PF4 busbars. All coils are charged with peak working current (TF is 68 kA, PF is 52 kA, CS is 45 kA, CC is 10 kA), while the plasma current is zero (quenching), a 52 kA current is applied on the PF4 busbars, and the pair of PF4 busbars consist of a loop, as shown in Fig. 2. The color codes and arrows are used to supply current source data for magnetic field problems, represents a current distribution in the model. The currents are used to calculate a source magnetic field intensity.

This analysis is made in the global Cartesian coordinate system, X axis is the transverse direction of the busbars

Table 1 Maximum of magnetic flux density (B) distribution

Region	Bx	By	Bz	Bsum
Busbar of PF4	−0.749	0.287	0.410	0.754

Bsum is total of maximum of magnetic flux density Bx, By and Bz

section, Y axis is the axial direction of the busbars on CFT, and Z is the vertical direction.

Results of Magnetic analysis

Table 1 gives a summary of the magnetic field distribution of the PF4 feeder. Here: Bsum is total of Maximum of magnetic flux density Bx, By and Bz; others are maximum of magnetic flux density (B) distribution in different direction respectively.

And Fig. 3 gives the distribution of Lorentz force on the PF4 busbars. The distribution of Lorentz force (Q) can be calculated by Eq. (1) from the element force (F_{em}) and element length (L_{em}). The maximum moment(M) is calculated by Eq. (2) if the busbar between two supports (L_{sp}) would be considered as a beam. So the relation between allowable stresses ([σ]) with moment can be shown in Eq. (3), the section modulus is W. And the reasonable distances between two busbar supports can be calculated, in Eq. (4).

$$\mathrm{Q} = \frac{F_{em}}{L_{em}} \tag{1}$$

$$\mathrm{M} = \frac{Q \times L_{sp}^2}{8} \tag{2}$$

$$\sigma_{\max} = \frac{M}{W} \leq [\sigma] \tag{3}$$

$$L_{sp} \leq \sqrt{\frac{8 \cdot [\sigma] \cdot W}{Q}} \tag{4}$$

The dense supports are required in ICF region because of the high EM force, while in both of CFT and SBB regions, EM force is smaller than the ICF region. To minimize the heat loads to the busbars, as well as the cryo-pipes, fewer supports is proposed. So a balance between mechanical strength and thermal insulation should be achieved. In order to win the results, peak Lorentz force in each region is used to calculate the space of border upon busbar supports. And from analysis results, 0.7 m is chosen as the spaces between supports in CTB and SBB and CFT of PF4 feeder; 0.5 m is chosen in ICF.

Mechanical analysis model for PF4

After spaces between busbar supports of PF4 feeder have been design, mechanical analysis should be done to check the structural strength and displacement of PF4 feeder system. This model describes the mechanical analysis of all crucial components in PF4 feeder system under the worst Lorentz force and 4.5 K operating scenario which is defined in the Feeder Design Description Document [1].

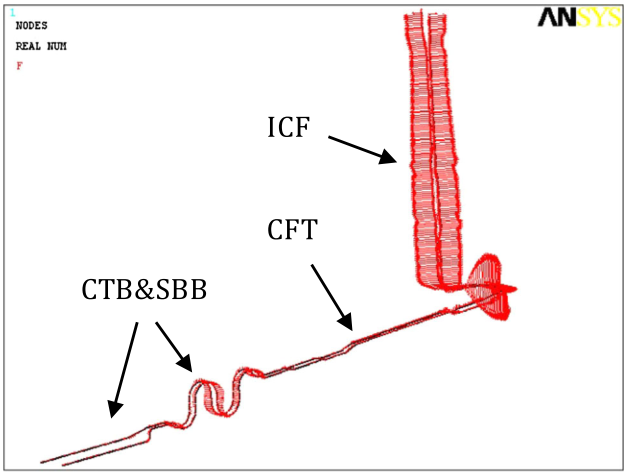


Fig. 3 Lorentz force on the PF4 busbars

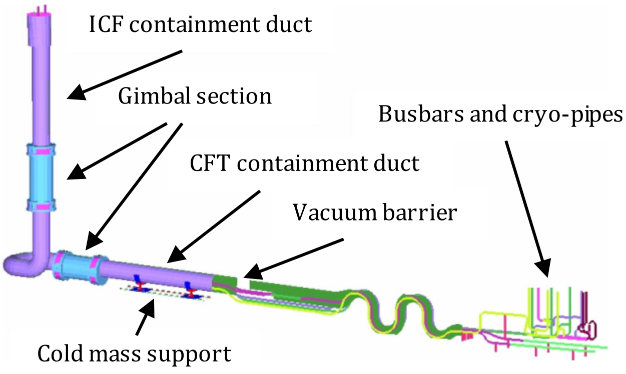
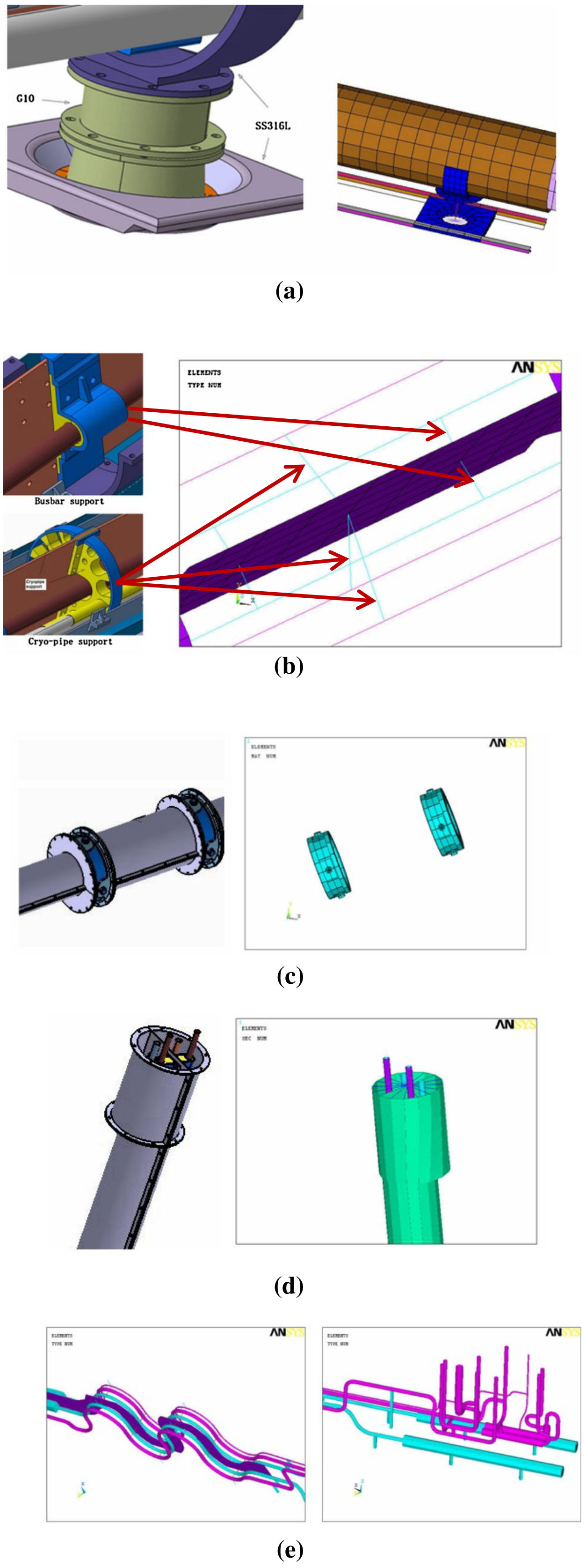


Fig. 4 PF4 Feeder global mechanical model

Firstly the Lorentz force on the busbar solid element from the magnetic analysis should be transferred to the busbar beam element in the mechanical analysis. Then the other components are added into the model to check the strength and displacement of critical components in this busbar support arrangement. In this step, the key components, including in the CTB and SBB, CFT, ICF, and other boundary conditions and loads, including the gravity, low temperature and coil terminal displacements, are applied [1].

Shown in Fig. 4, the FE (finite element) model contains all the critical components like the busbars, cryo-pipes, CFT cold mass supports, containment ducts, separate plates and the gimbals (between the CFT containment duct and ICF containment duct are modeled as a simplified geometry of



◀**Fig. 5** Detail design and analysis models of PF4 feeder. **a** Detail design and analysis model of CFT cold mass supports. **b** Detail design and analysis model of busbar/cryo-pipe supports. **c** Detail design and analysis model of gimbals. **d** Detail design and analysis model of ICF terminal. **e** Analysis model of busbars and cryo-pipes for CTB and S-bend box

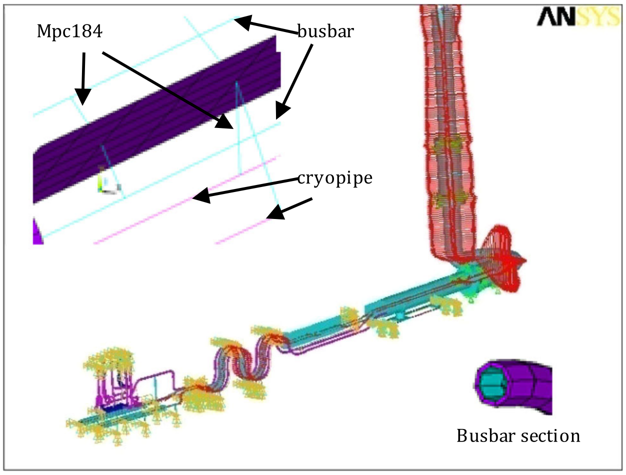


Fig. 6 Boundary conditions and loads description

hollow cylinder, while the flexibility of rotation is kept). This is a huge system, so simplification is applied to meet the calculation power of the computer. The detail design and analysis models of PF4 typical components are shown in Fig. 5.

Boundary conditions and loads for mechanical analysis

These analyses also are made in the global Cartesian coordinate system and same with magnetic analysis.

The busbar consists of superconducting cable, stainless steel jacket and insulation layer from inner to outer respectively. The cable can be ignored in analysis model because it is much softer than other two parts (busbar section shown in bottom-right corner on Fig. 6, blue part is a stainless steel jacket, and purple part is an insulation layer). The support of busbar is stiffer than busbar, and an Mpc184 element is used to connect the busbar to the separate plate as a support. Meanwhile, the contact element Contac178 is chosen between the Mpc184 and the busbar. The same elements also are employed in cryo-pipes (shown in up-left corner on Fig. 6).

The ends of busbar at the dry box are fixed, and the ends at the ICF terminal joint are applied with the PF4 coil displacements (radial −33.4 mm to the cryostat centre, vertical −9.2 mm upwards and toroidal 20.72 mm) [1]. The ends of cryo-pipe at vacuum barrier to cryogenic distribution are fixed, and another ends at the ICF terminal joint are applied with the coil displacements same with the busbars. SBB separate plate at CFT vacuum barrier are fixed, at the same time, all DOF constrained without slide along feeder axis. The bottom sled of the CFT cold mass support is fixed, and the support can move in feeder axial direction by contact element. The top of the ICF terminal boxes are applied with the coil displacements same with the busbars.

Standard earth gravity 9.8 m/s^2 is applied in the vertical direction to simulate the standard gravity load. Temperature of 4.5 K is applied on the busbars, cryo-pipes to check the thermal shrinkage, and temperature of 10 K is applied on the containment duct and the separate plate [1], the reference temperature is set as 300 K [6]. Lorentz force from the magnetic analysis is applied on the busbars (see Fig. 6). Lorentz forces are shown in red areas. The fixed boundaries are shown in yellow. And others are defined color same with Fig. 4.

Mechanical analysis results

The mechanical analysis aims at assessing busbar supports of PF4 feeder system and ensuring the structure, including busbar jacket, containment duct and cryo-pipes, not be damaged in excessive deformation, stress and so on. Allowable stresses in this structure are assessed in accordance with Magnet Structural Design Criteria Part 1.2FMHHS_v1.0. For structure materials [7], the design stress intensity S_m determined by:

$$S_m = 2/3S_y \tag{5}$$

here S_y is the yield strength;

Primary stresses intensities P_m and $P_L + P_b$ calculated by elastic analysis for the design conditions should satisfy the following relation:

$$\mathrm{P}_m < S_m \tag{6}$$

$$P_L + P_b < 1.5S_m \tag{7}$$

here P_m is the general primary membrane stress intensity; P_L is the local primary membrane stress intensity; P_b is the primary bending stress intensity.

For the busbar SS316L jacket, the structure intensity is more important than others, so the limit for its sum of membrane and bending stress is 1.3Sm.

Table 2 is the mechanical results of key components: P_m, P_L, P_b and their maximum value of displacements under all loads (including the gravity, cool-down, coil displacement, Lorentz force). Table 3 shows the design values, calculated values and results checked of stress intensity on these key components. From here it can be seen that all mechanical properties satisfy structural design criteria and the displacements(shown Table 4) also cannot damage their structure because the S-bends will have a deformation due to the thermal shrinkage and gravity, the bends are tensed and the busbars are protected. Also cryo-pipes are.

Summary

For the purpose of balance between mechanical strength and thermal insulation performance to the busbars as well as the cryo-pipes, the quantity and the spaces between supports in the 4th PF feeder have been studied and the

Table 2 Mechanical results under EM force + cool down + gravity

Component	Stress intensity/MPa	Displacement/m	Membrane stress/MPa	Bending stress/MPa
Busbar jacket	351	0.0446	32.1	324.5
Containment duct	299	0.0503	−83.6	−209.5
Cryopipe	171	0.0476	10.4	108.8

Table 4 Displacement of the components under EM force + cool down + gravity

Component	X-displacement/m	Y-displacement/m	Z-displacement/m
Containment duct	−0.0403	0.0220	−0.0399
Busbar jacket	−0.0379	0.0249	−0.0396
Cryopipe	−0.0369	0.0220	−0.0363

Table 3 Mechanical stress check under EM force + cool down + gravity

Component	Temperature (K)	S_y (MPa)	$S_m = 2/3S_y$ (MPa)	P_m (MPa)	$P_L + P_b$ (MPa)	$1.5S_m/1.3S_m$ (MPa)	Stress Check
Busbar Jacket	4.5	700	466	351	356.6	$1.3S_m = 606$	ok
Containment duct	10	494	329	299	293.1	$1.5S_m = 493$	ok
Cryopipe	4.5	500	333	171	119.2	$1.5S_m = 499$	ok

detail design confirmed. To get real magnetic force load under the worst scenario, an electric–magnetic coupled analysis which includes the busbars and the coils is performed, then the Lorentz force result is imported into the mechanical analysis, applied on the busbars, meanwhile the supports, the containment duct and other critical components are contained in the finite element model (FEM) to check the full system performance under Lorentz forces, earth gravity and thermal contract at 4.5 K. And from analysis results, the spaces between supports in CTB and SBB, CFT of 4th PF feeder are 0.7 m; in ICF are 0.5 m. And the mechanical stresses on different key components are checked (see Table 3), the mechanical stresses, displacement and deformation on different key components are checked. In view of these results, it can be known that present busbar support design of PF4 feeder can meet requirement of ITER [1].

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