# The Engineering Commissioning of the Magnets System On HL-2M Tokamak

Xiaolong Liu, Guangsheng Li, Qiang Li, Hui Zou, Yin Qiu, Yanong Shan, Lijun Cai, and Xin Chen

***Abstract*—HL-2M tokamak is one of largest magnetic confinement fusion devices designed and constructed by Southwestern Institute of Physics (SWIP), China National Nuclear Corporation (CNNC), the first plasma was obtained on December, 4th, 2020. The magnets system which plays an important role for the plasma confinement consists of 20 toroidal field (TF) coils and 18 poloidal field (PF) coils. The magnets system commissioning was carried out by two phases: self-commissioning and integrated commissioning. The first phase: self-commissioning including joint resistance commissioning, turn to turn insulation commissioning, ground insulation commissioning, deionized water sealing commissioning was accomplished during the installation and test of the magnets system. The second phase: the integrated commissioning with power supply system, ground system, measurement and data acquisition system, plasma control system, interlock and safety system was accomplished based on the results of the first stage. The total commissioning of magnets system in HL-2M tokamak for the first plasma have been accomplished successfully.**

***Index Terms*—Coils, HL-2M, magnets, plasma, tokamak devices.**

## I. Introduction

The commissioning of the magnets system on HL-2M tokamak started in Oct, 2020, and was completed in November, 2020 at SWIP site in Chengdu. HL-2M tokamak is a flexible experimental and operational platform with good accessibility to plasma. The major designed parameters of HL-2M, as shown in Table I, are major radius 1.78 m, minor radius 0.65 m, toroidal field 2.2 T, and plasma current 2.5 MA with a flexible plasma configuration [1], [2]. The cross-sectional view of the HL-2M tokamak is shown in Fig. 1.

The magnets system consists of 20 toroidal field (TF) coils and 16 poloidal field (PF) coils, copper alloy is used as the conductor material for both TF and PF coils, while deionized water is used for cooling these conductors. The TF coils system can provide a magnetic field of 2.2 T at plasma center when the TF coils current is 140 kA, and also be able to provide a 3 T magnetic field at plasma center with TF coil current of 191 kA [2],[3].

The TF coils provides the main confining magnet field for the plasma. The basic form of the TF coil is a D-shaped constant tension configuration, and each coil consists of 7 turns copper alloy splice plates, i.e., 7 turns of conductors. The 7 turns of a D-shaped coil wound a solenoidal type of configuration. The 140 turns electrically connected in series. Each D-shaped TF coil incorporates 3 sections: The L-shaped center section, the bar-shaped upper section and the C-shaped outer section, where the cross-section view of a TF coils is shown in Fig. 2. The 0.8 mm thick epoxy impregnated glass tape is used to bond the copper conductors together, and the design value of turn-to-turn shear stress strength is 14 MPa, also the epoxy impregnated glass tape is used as the insulating material between the copper conductors. Nine additional clamp bolts with insulated casing shown in Fig. 2, are used to link and fasten the 7 turns of C-shaped copper conductors of the outer section by penetrating the 7 turns of copper conductors, meanwhile short circuit among the 7 turns are avoided by the insulating casing. The 20 L-shaped center sections are bonded together by epoxy impregnated glass fiber belt to form a monolithic structure which

TABLE I
MAJOR PARAMETERS OF HL-2M TOKAMAK

| Parameter | | Unit |
|---|---|---|
| Plasma current | 2.5 (3) | MA |
| Major radius | 1.78 | m |
| Minor radius | 0.65 | m |
| Aspect ratio | 4.1 | |
| Flux swing | >14 | Vs |
| Toroidal field | 2.2 (3) | T |
| Elongation | 2 | |
| Triangularity | >0.5 | |
| Pulse length | 3-5 | s |

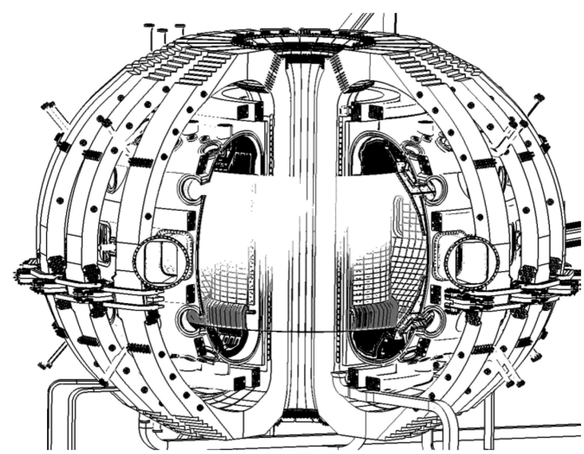

Fig. 1. The cross-section view of HL-2M tokamak. The TF coils are located in the outermost, the vacuum vessel is surrounded by the PF coils set. The height of machine is about 5 m, diameter is around 6 m. The total weight, including the coils, vacuum vessel and the support frame is about 400 tons.

Manuscript received March 15, 2021; revised May 20, 2021 and May 20, 2021; accepted May 26, 2021. Date of publication June 21, 2021; date of current version July 13, 2021. *(Corresponding author: Xiaolong Liu.)*

The authors are with the Center for Fusion Science, Southwestern Institute of Physics, China National Nuclear Corporation, Chengdu 610225, China (e-mail: liuxl@swip.ac.cn; leegsh@swip.ac.cn; liqiang@swip.ac.cn; zhouh@swip.ac.cn; qiuy@swip.ac.cn; shanyn@swip.ac.cn; cailj@swip.ac.cn; chenx@swip.ac.cn).

Digital Object Identifier 10.1109/TASC.2021.3091057

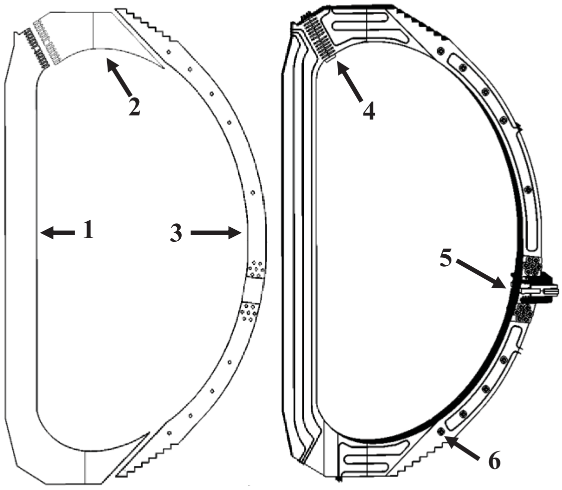


Fig. 2. The cross-section view of a demountable TF coil, in which, “1” is the L-shaped center section, “2” is the bar-shaped section, “3” is the C-shape section, is the bar-shaped section, “4” is demountable joint structure, “5” is the interconnection between the TF coils, “6” is the clamp bolts with insulated casing, there are 9 clamp bolts for a C-shape section. The weight is a TF coil is 9 tons.

is called centerpost, i.e., the 20 L-shaped sections are assembled as a cylinder structure, and then 25 mm thick weft-less belt is wounded layer by layer on the straightened section of the cylinder structure. The single layer of the weft-less belt is with 0.3 mm thickness, and 50 mm width, the tension strength of the weft-less belt is over 600 MPa, and 300 MPa tension force was applied when the weft-less belt was wounded. The bar-shaped section is attached to L-shape center section by a demountable finger joints structure from one side, and attached to upper side of the C-shaped section by demountable electrical joints from the other side. The lower side of the C-shaped section and L-shaped center section are attached together by demountable electrical joints. In this case, the bar-shaped section and the C-shaped section both are demountable, and the vacuum vessel and the PF coils can be easily accessed in the D-shaped TF coils from the space when the bar-shaped upper sections and C-shaped sections are removed. This design was determined since it is convenient to replace the PF coils and vacuum vessel.

The PF coil set, which consists of 2 central solenoid (CS) coils and 16 PF coils, designed on the bases of hybrid PF system for plasma initiation and sustainment. The position distribution of the PF coil system around the vacuum vessel and TF coils is as Fig. 3. The PF coil system provides more than 14 Vs flux swing and inductively sustains the plasma current of 2.5 MA for 3∼5 seconds. Concretely, the CS coils provide the main voltage-second for Ohmic heating, and the 16 PF coils (PF1-PF8) are used to control the shape and position of plasma. The coils’ location was optimized to obtain the various configuration of plasmas, such as snowflake diverter [4], limiter, double null, single null, etc.

The CS coils are comprised of 2 parallel sub-coils, CSA and CSB, where the CSA and CSB coils are 48 turns of solenoid type coils. CSA and CSB coils are wounded in two layers and interlaced with each other around the outer surface of centerpost. The CS coils with centerpost are baked and cured as an integrated structure. The maximum operational current of CSA and CSB coils are 110 kA. The PF1-4 coils, which include 4 lower side

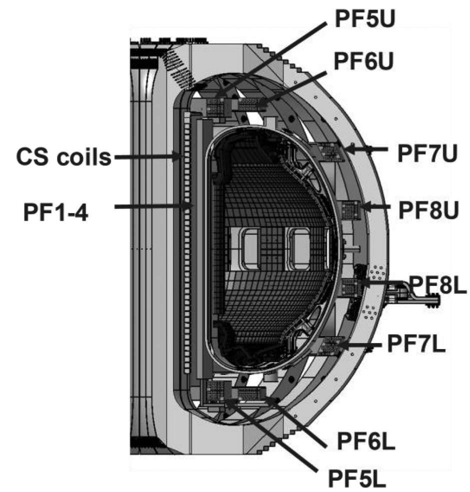


Fig. 3. The cross-section view of PF coils.

TABLE II
MAJOR PARAMETERS OF MAGNETIC FIELD COILS

| TF coils | | Unit |
|---|---|---|
| Rated current @ 2.2 T | 140 | kA |
| Number of turns | 140 | |
| Number of coils | 20 | |
| Resistance @ 50° C | ~4 | mΩ |
| Inductance | 32 | mH |
| Toroidal field | 2.2 (3) | T |
| Duration | 14 | s |
| **PF & CS coils** | | **Unit** |
| Number of PF & CS coils | 18 | |
| Turn to turn insulation | 1000 | V |
| Rated current of CSA & CSB | 110 | kA |
| Number of turns of CSA & CSB | 48 | |
| Rated current of PF1-4 | 15 | kA |
| Number of turns PF1-6 | 28 | |
| Rated current of PF5-8 | 40 | kA |
| Number of turns of PF7-8 | 26 | |

and 4 upper side coils, are symmetrically arranged by the middle plane of HL-2M tokamak, coaxial with the CS coils. PF1-4 coils are combined into a hollow cylinder by impregnation. The PF5-8 coils which include 4 lower side coils (PF5L, PF6L, PF7L & PF8L) and 4 upper side coils (PF5U, PF6U, PF7U & PF8U) are independent pancake type coils. Each coil of PF1-6 contains 28 turns, each coil of PF7-8 contains 26 turns. The maximum operational current of PF1-4 coils and PF5-8 coils are 15 kA and 40 kA, respectively. The PF coils use rectangular section with round cooling channels in the section center. The turn-to-turn insulation comprises of Polyimide film and glass fiber type, and impregnated with epoxy resin. The CS coil use medium rubber mica tape as the turn-turn insulation material and high temperature baking was carried out for curing. The major parameters of the magnetic field coils are summarized in Table II.

## II. Self-Commissioning

The objectives of self-commissioning were to verify whether the performance satisfy the design requirements. The self-commissioning provided the data in the facility test phase for the confrontation with the assembly phase. Since the engineering

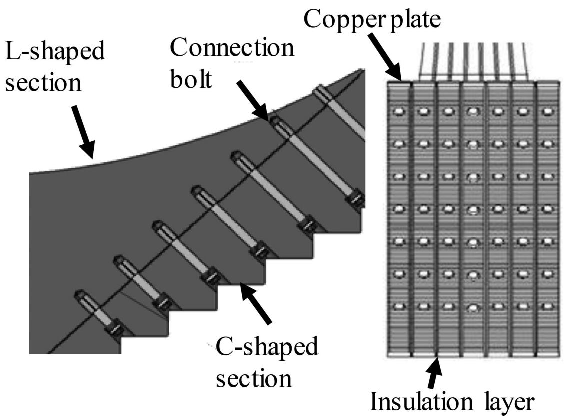


Fig. 4. The connection between L-shaped center section and C-shaped outer section.

complex of HL-2M tokamak, some test, such as turn-to-turn insulation test for the PF coils, can be only carried out during self-commissioning phase. The self-commissioning was synchronized with all the installation and assembly process of tokamak machine.

The self-commissioning was started before the assembly of centerpost, when all the coils were delivered to coil assembly hall on SWIP site, and it is accomplished when all the TF coils were installed in the machine. Electrical insulation, electrical conductivity and the deionized water-cooling seal performance are the key issues for the magnets system during self-commissioning phase.

### A. TF Coils Self-Commissioning

The turn-to-turn insulation of the three sections of TF coils was continuously measured before the three sections were assembled together to form a D-shape coil. The connection between L-shaped center section and C-shaped outer section is shown in Fig. 4, where the left side one is the side view of the bolts connection, and the right side one is the front view of the connection surface of the L-shaped center section, which the 7 turns of copper plates, the 6 insulation layers and 7∗7 connection bolt holes are shown in.

The withstand voltage of insulation layer between the copper plates is designed to be 500 V DC. Daily tests were accomplished to get the experience of the insulation resistance under different environmental humidity, temperature, and atmosphere pressure. The turn-to-turn insulation of three sections was tested by 500 V DC separately before installation, and also tested by 250 V DC after the bar-shaped section assembled together with centerpost. The turn-to-turn insulation test was not carried out after D-shaped TF coil closured because of two reasons. First, the extension and alignment of the insulation layer were guaranteed by connection bolts precise positioning shown in Fig. 4, i.e., the turn-to-turn insulation layers from different sections are aligned by precise positioning of the connection bolts, without malposition which may lead turn to turn short circuit. Second, the nominal terminal voltage of TF coils is 1660 V, and the operational turn-to turn voltage is only about 1660V/140 = 12 V, which is much lower than the design level.

At self-commissioning phase, the ground insulation for centerpost was focused on the insulation between the copper alloy plates and the stainless-steel shielding layer, which lays on the outer surface of the centerpost, the minimal distance between the plates and shielding layer is about 2 cm, the designed ground insulation level 6 kV DC was been tested. When the installation of TF coils was finished, the grounding insulation were be tested by 6 kV DC again between the TF coils and all the metallic components nearby. In summary, the grounding insulation test were passed successfully.

The electrical conductivity of TF coils was tested under the condition that the nominal tightening torque was loaded on the related connection bolts. First, after the bar-shaped section was installed on the centerpost, the measured contact resistance around was 500 nΩ of each finger joint, and the measured results were consistent with the Finite Element Method (FEM) analysis. The contact resistance between the bar-shaped section and the C-shaped section, the contact resistance of the interconnection, was also measured to verify the assembly effectiveness, the measured values were consistent with the experimental results on a protype of TF coil. Second, the measured resistance around 180 $\mu\Omega$ of each TF coil and the total resistance 3.6 mΩ of 20 TF coils in series connection were measured to ensure that the compliance with theoretical calculation by FEM method.

Before centerpost assembly and after it was delivered to the installation hall, the water sealing test for all cooling channels inside copper plates with their connectors was also carried out to ensure that there is no leakage at 1 MPa pressure.

### B. PF and CS Coils Self-Commissioning

The geometrical measurements of the PF coils were carried out by laser tracker. The installation deviation was controlled in 1 mm in horizontal plane and 1 mm in vertical axis.

The PF and CS coils are insulated to a transient voltage of 1000 V/ turn. The turn-to-turn insulation commissioning of PF and CS coils was carried out based on the high voltage impulse technology which is widely used in electric machinery industry. The applied voltage on the 2 terminals of coil was carefully adjusted to raise up step by step for safety, and the response waveforms of different applied voltages levels must be proportional.

The applied impulse voltage on the terminals is ∼30 kV for PF1-8 coils' turn to turn insulation test. The 26 kV high voltage impulses were applied on the 2 terminals of CSA and CSB coils, respectively. The impulse responses of CSA and CSB coils is shown in Fig. 5, since the symmetry of CSA of CSB, since there is only slightly difference between the responses, it shows that the turn-to-turn insulation tests are passed. The turn-to-turn insulation test for the PF coils were carried out just before hoisting and positioning, and it was not able to test again after the PF coils were positioned since the large number of distributed metallic components including the vacuum vessel, support frame for coils, craft platform, etc., were around the machine.

The ground insulation test was applied after the PF coils were positioned as the same strategy of the TF coils; the ground insulation test voltage was 6 kV DC, which applied between the copper conductor and the shielding layer of PF coils.

The resistance of each PF coil was examined with the factory test result to avoid any potential conductive damage, in this case, the onsite resistance measurements were passed.

The deionized water sealing test also carried out before and after positioning under 3 MPa water pressure.

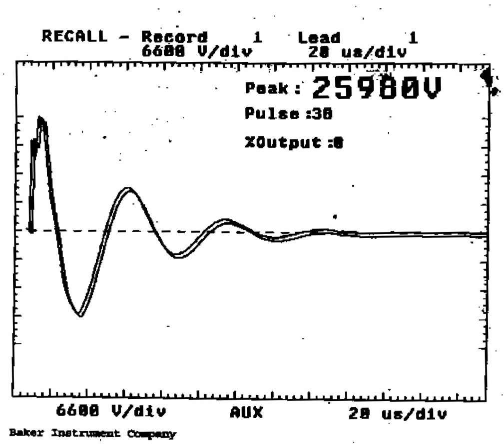


Fig. 5. The high voltage impulse response of the CSA and CSB coil. The peak voltage applied on CSA and CSB is 25980 V, the time scale is 20 $\mu$s/div.

TABLE III
MAJOR STEPS OF INTEGRATED COMMISSIONING

| Step | Content |
|---|---|
| 1 | Subsystems' self-inspection |
| 2 | No-load commissioning (without coils) |
| 3 | Independent load commissioning for single coil |
| 4 | Subsystems' self-inspection for first plasma |
| 5 | Joint load commissioning for multiple coils |

## III. INTEGRATED COMMISSIONING

The integrated commissioning was carried out on a tight schedule for the first plasma in the end of 2020. The integrated commissioning of the coils with other subsystems was the final step for the first plasma of HL-2M tokamak. All sub-works were commenced as parallel as possible, e.g., even the C-shaped outer sections were in the installation process, the self-commissioning of the power supplies for TF coils had been started. A Detailed inspection and commissioning plan was created.

The integrated commissioning for the coils was classified into the following five main steps, which is summarized in Table III. The first step was Subsystems' self-inspection: such as magnets system, power supply system, ground system, measurement and data acquisition system, plasma control system (PCS) [5], interlock and safety system, perform their self-inspection according to the tight schedule. The second step was the no-load commissioning for the coils with PCS and power supplies, it means that all energization conditions are available, but the coils are not powered. During no-load commissioning, control and communication tests were carried out between the subsystem with PCS and interlock and safety system. The third step was independent load commissioning for single coil. The coils were energized individually and successively by their respective power supplies. The fourth step was the subsystems' self-inspection of whole machine for first plasma, compared with the first step, more sub systems, such as plasma diagnostics systems, vacuum system were inspected during this step. The accessible connection bolts in the TF coils were be fastened again in order to ensure the electrical connection. The ground insulation was tested again on the TF and PF coils by 1000 V DC to verify that the coils were floating apart from earth, and only one grounding point for each coil was remained when it was connected with

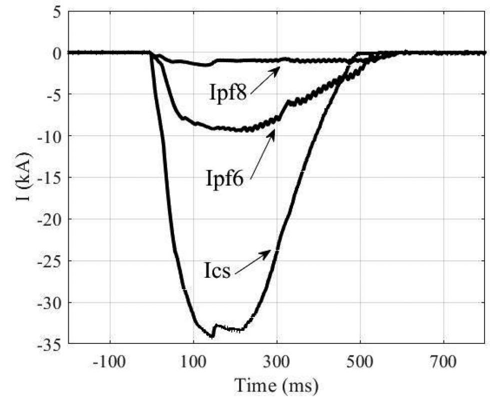


Fig. 6. The current waveform of PF6 ,PF8 and CS coils in shot number 214.

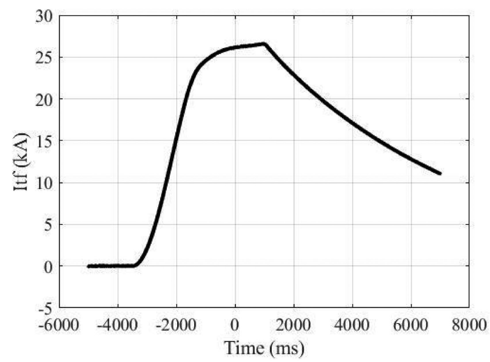


Fig. 7. The current waveform of the TF coils in shot number 214.

grounding system. The fifth step was joint load commissioning for multiple coils, the commissioning coils TF, CS, PF6 and PF8 were energized together during the same tokamak operation shot, and PF1-4, PF5 and PF7 were not energized, because of the tight schedule. If the other necessary conditions were available, the working gas $H_2$ in vacuum vessel could be broken down and ionized into plasma by the electrical field which generated by the PF coils.

For the integrated commissioning, the critical steps were the second and third ones, since the "soft" problems mainly were be found in the two steps. The integrated commissioning was divided into 2 phases, the first phase was the commissioning of the coils for the first plasma, the final phase was the commissioning of the rest coils after first plasma of HL-2M tokamak.

For the detail commissioning philosophy, the coils were tested by increasing the current level from zero in steps, while the assistance system, such as ground fault protection system for both TF and PF coils, conductor temperature monitor for TF coils, the pre-stress monitor for TF coils and displacement monitor for the C-shaped outer section were activated. The PF6, PF8 and CS coils were energized separately to verify the current control proposal, secondly, the PF6, PF8 and CS coils were activated together to acquiring a null field in the vacuum vessel, and the current control algorithm was improved base on the mutual inductance among the PF6, PF8 and CS coils. The current waveform of PF6, PF8 and CS coils in shot number 214 is shown in Fig. 6. Similar philosophy for the commissioning of TF coils was applied, and the operational result is shown in Fig. 7. During operation, the $I^2t$ of TF coils was calculated shot by shot as a threshold, during commissioning, $I^2t$ was limited to $7.8 * 10^{11}$ $A^2s$, because the TF coils were naturally cooled during commissioning. The temperature of TF coils was estimated and measured shot by shot, and the temperature rise of was limited to 40°C in order to protect the epoxy and also avoid the over stress by temperature rise.

## IV. Conclusion

The design, construction of the magnets system lasted for 8 years. The engineering commissioning of the magnets system on HL-2M tokamak was successfully achieved for the first plasma. The remarkable aspects of commissioning were that no major problems occurred during commissioning. Lots of lessons were learned from the commissioning. First, a fully detailed commissioning plan must be made, and all the necessary items must be validated on time, since the schedule was quite tight. Second, the insulation performance was the critical issue, especially the turn-to-turn insulation of TF coils must be carefully reviewed in different phase. Third, the current and voltage increasing level of the coils must be controlled in steps during energization, and completive protection philosophy including over current, over voltage, and ground fault protection must be considered to ensure the operational safety. The exhaustive quality control, well-organized schedule and carefully inspection were the basis of commissioning for the first plasma of HL-2M. Moreover, the turn-to-turn insulation test principle of PF coils could be extended to the super conductive coils, and also the commissioning could be a reference for some super conductive coils, especially for the super conductive tokamaks.

## Acknowledgment

The Authors would like to thank all the staffs who contribute for the design, construction, installation, and commissioning of HL-2M magnets system, especially thank the colleagues from plasma control division and power supply division for their help.

## References

[1] Q. Li *et al.*, "Design and development of magnets for HL-2M tokamak," in *Proc. IEEE Int. Conf. Appl. Supercond. Electromagn. Devices (ASEMD)*, Shanghai, China, 2015, pp. 597–598, doi: 10.1109/ASEMD.2015.7453718.

[2] X. R. Duan *et al.*, "Progress in fusion technology at SWIP, *Fusion Eng. Des.*, vol. 109–111, Part A, 2016, pp. 1022–1027.

[3] L. J. Cai *et al.*, "Electromagnetic loads prediction and structural analysis of HL-2M toroidal field coils," in *Proc. IEEE 25th Symp. Fusion Eng.*, San Francisco, CA, USA, 2013, pp. 1–5.

[4] G. Y. Zheng, X. Q. Xu, D. D. Ryutov, Y. D. Pan, and T. Y. Xia, "Magnetic configuration flexibility of snowflake divertor for HL-2M," *Fusion Eng. Des.*, vol. 89, no. 11, 2014, pp. 2621–2627.

[5] J. Zhou *et al.*, "The central control system for first plasma campaign HL-2M," *Fusion Eng. Des.*, vol. 155, 2020, Art. no. 111565.