Progress of the EAST Project in China

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Abstract. The Experimental Advanced Superconducting Tokamak (EAST) project is one of the National Mega-Projects of Science Research of China, which was approved by Chinese government in 1998. EAST is a full superconducting tokamak with an elongated plasma cross-section. The mission of the project is to widely investigate both of the physics and the technologies of advanced tokamak operations, especially the mechanism of power and particle handling for steady-state operations. The basic requirements for the EAST tokamak are full superconducting coils, suitable inductive current system, continuous working non-inductive current driven and heating systems, flexible operation scenarios, flexible J(r) and P(r) control, reliable and fast plasma positioning and shaping control, changeable plasma facing components, advanced divertor and diagnostics. Significant progress of the EAST project has been achieved during last two years. The R&D programs, mainly focused on the superconducting magnets, have processed successfully. The prototypes of main parts have been fabricated and qualified. Most of the key parts of the machine have been delivered to the assembly site. The assembly of the device has begun. It is planned to obtain the first plasma in 2005. The detail information of the testing results of superconducting magnets will be given in this paper. The assembly plan and the experimental plan will be introduced, too.

1. Introduction

A National Mega-Project named originally the HT-7U superconducting tokamak had been approved in 1998 by Chinese government. The name of HT-7U has been renamed to be Experimental Advanced Superconducting Tokamak (EAST) in 2003. The core of the EAST project in the engineering phase is to build a full superconducting tokamak with a non-circle cross-section of the vacuum vessel at the institute of plasma physics, the Chinese academy of sciences (ASIPP). The scientific and the engineering missions of the EAST project are to study physics issues of the advanced steady-state tokamak operations and to establish technology basis of full superconducting tokamaks. The cross-section of the machine inside the EAST hall is shown in FIG. 1 and the main parameters of EAST are listed in Table I [1]. The basic physical and engineering features of EAST are as following:

- Both toroidal field (TF) and poloidal field (PF) will be provided by superconducting magnet systems, which will ensure the ability to confine, shape and control the plasma for a long pulse or even steady-state.
- Continuous working (CW) non-inductive plasma current drive and heating systems make it possible to sustain high performance plasmas with J(r) and P(r) control in steady-state.
- The PF system with twelve individual power supplies for each PF coil and non-circle cross-section design offer flexibility and reliability to shape and control plasmas with big elongations and triangularity, especially to demonstrate single-null, quasi double-null and double null configurations, seeing FIG. 2.
- Real time data collection and feedback for steady-state profile control.
- Active cooling and changeable plasma facing components (PFC) and divertors make power and particle handling study very effectively.
- Advanced plasma facing materials (PFM) and wall conditioning technique will make contributions to future tokamak reactors.
- EAST will have advanced diagnostic measurements.

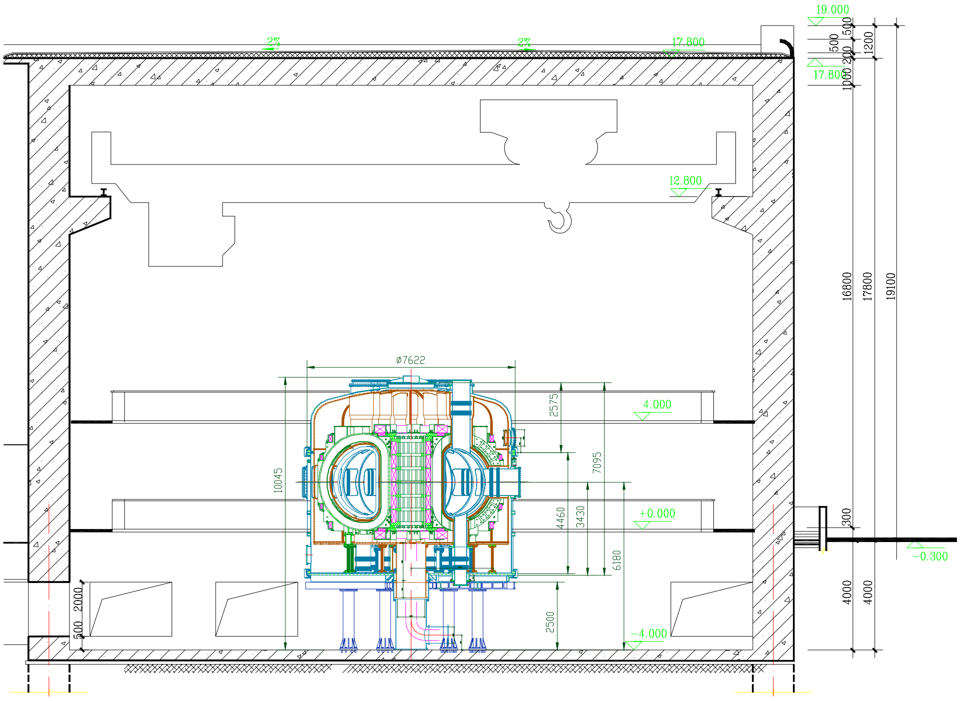
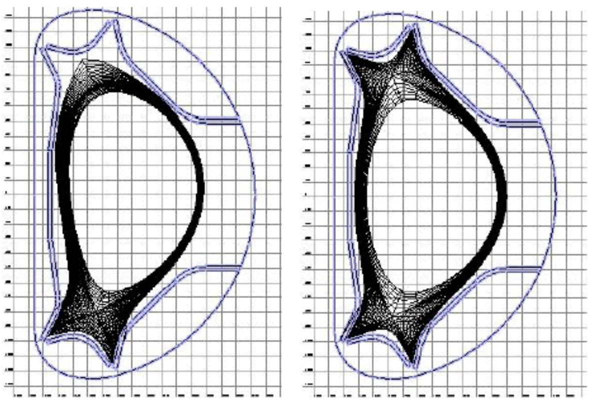


FIG. 1. The cross-section of the EAST machine inside the EAST hall

TABLE I: THE MAIN PARAMETERS OF EAST

Toroidal Field, B_o	3.5 T
Plasma Current, I_P	1 MA
Major Radius, R_o	1.7 m
Minor Radius, a	0.4 m
Aspect Ratio, R/a	4.25
Elongation, K_x	1.6 - 2
Triangularity, δ_x	0.6 - 0.8
Heating and Driving (in the first phase):	
ICRH	3-3.5MW
LHCD	3.5 MW
ECRH	0.5 MW
Pulse length	1- 1000 s
Configuration:	Double-null divertor Single-null divertor Pump limiter



(a) *(b)*

FIG. 2. The configurations of Single-null (a) and Double-null (b) of EAST

The design of the cryogenic and refrigerator system of EAST has a further update ability to reduce the liquid helium temperature from 4.5 K to 3.8 K and the design criterion of the TF magnet system is based on the peak field of 6.72 T which is updated TF operation with 4.0 T at the major radius of 1.7 m, instead of 5.8 T with 3.5 T of nominal operation. EAST could be the first tokamak machine with both all superconducting magnets and actively cooled in-vessel components in the world, if its construction could finish in 2005. The EAST project will promote the fusion research in China within next ten to twenty years and set a base of next ambitious fusion project of China. It surely will make a contribution to the future steady-state advanced tokamak reactor in the world.

2. Important Progresses

The physical and engineering design of EAST were completed in 2001. The significant progresses of a so-called pre-physics experimental program related to EAST have been achieved on the HT-7 superconducting tokamak, especially by achieving about 240 s long pulse in the last operation campaign from April to June of 2004. The technologies of long pulse discharges for plasma initiation with low loop voltage, wall conditioning, plasma facing material, non-inductive current drive and heating, plasma control and data acquisition and processing have been developed very well [2].

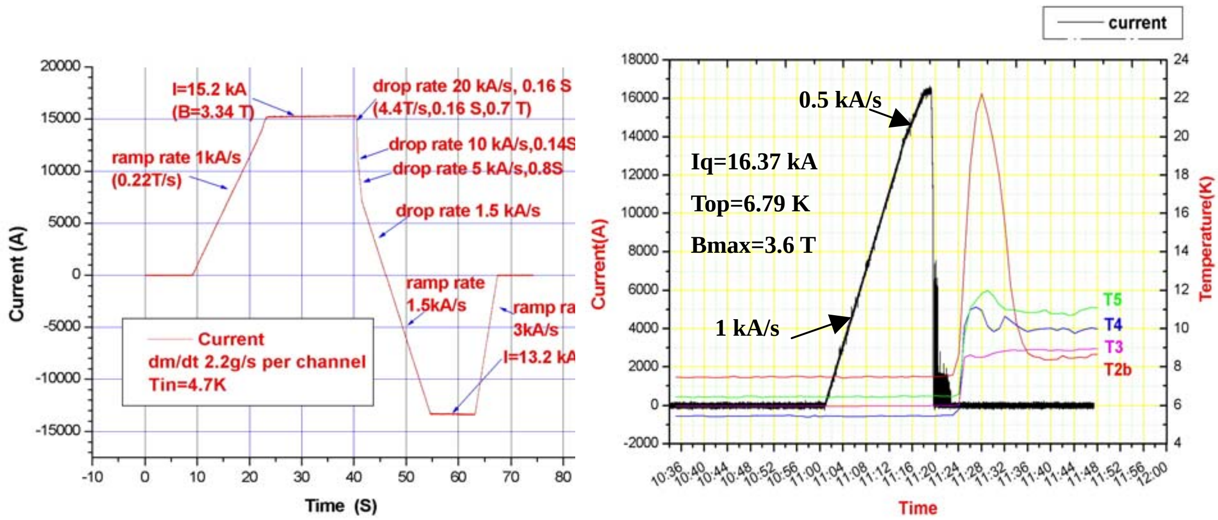
The main tasks of the EAST construction are as followings:

- EAST buildings, including EAST machine hall and other appurtenant buildings
- EAST tokamak machine, mainly consisted of seventeen D-shaped TF superconducting magnets including one spare coil, thirteen PF superconducting magnets including one spare central solenoid (CS), vacuum vessel (VV), thermal shields (TS), cryostat vessel (CV) and support system
- 110 kV/83 MVA transmission line and transformer substation
- Cryogenic test facility system including a big cryostat, a cryogenic and refrigerator system, power supply systems and control and data acquisition systems
- 2 kW/4.5 K cryogenic and refrigerator system
- Power supply systems for TF, PF and plasma fast control
- Pumping and fueling systems
- In-vessel components, including first wall materials, divertor, electromagnetic measurement and fast feedback coils
- Water cooling system
- Plasma diagnostics
- Plasma control and data acquisition systems
- Current drive and plasma heating systems, such as lower hybrid current drive (LHCD), ion cyclotron resonance heating (ICRH), electron cyclotron resonance heating (ECRH) and neutral beam injection (NBI)

The R&D programs on EAST have been quite successful, which have been especially focusing on the EAST machine. Much attention has been paid on NbTi superconductivity engineering development, such as technologies of cable-in-conduit conductor (CICC) design, fabrication and test of sub-cables, short samples of CICC and model/prototype coils [3]. To use existing superconducting strands for accelerator, we have to suffer its lower copper ratio. According to optimisation calculations, the copper ratio of the EAST CICC must be increased from 1.38 to more than 5. Before the final design of the TF and PF CICCs was defined, several CICC design versions with additional separated pure copper strands had been analysed on their cryogenic stability performances. After short sample tests, three designs were defined as TF/CS/divertor coils and four big PF coils, separately.

Most of key fabrication procedures of superconducting magnets are carried by ASIPP. A 600 m CICC superconductor jacketing line, three special winding machines and a VPI facility had been developed and operating well at ASIPP from 2001. Up to June of 2004, totally 32 km CICC conductors have been fabricated, which is enough for all TF and PF coils including one spare TF coil and one spare CS coil. With high quality CICCs, up to now, seventeen windings of TF and thirteen PF coils have been fabricated. Among them, fourteen TF magnets with cases and joints have been completely machined, tested and delivered to the EAST assembly site. Twelve PF coils including four big PF coils of more than five meters in diameter are ready for assembly. The rest coils will be ready for assembly before the end of 2004.

To ensure the superconducting performances, all superconducting coils, except for four big PF coils, will be tested. Even four big PF coils had been qualified by testing a model coil made of same conductor in similar operation conditions. A test facility system that mainly includes a big cryostat of 3.4 m in diameter and 6 m in height, a power supply system of 80 MW and a cryogenic and refrigerator system of 500 W/4.5 K was set up and operated normally from 2002. The tests of the superconducting magnets, especially the test of one CS prototype coil that will suffer extreme flux changing at 7 T/s in 60 ms during plasma initiation, had shown quite good results in 2003. The typical test current scenario of CS is based on the similar $\int \dot{B}^2 dt$ with the operation scenario during the EAST plasma initiation. The results shown the coil is quite stable during fast discharge at maximal dump rate of 20 kA/s in 160 ms, shown in FIG. 3 (a). Due to the current limitation of the power supply system the quench current was detected as 16.4 kA with 6.8 K operation temperature, shown in FIG. 3 (b).



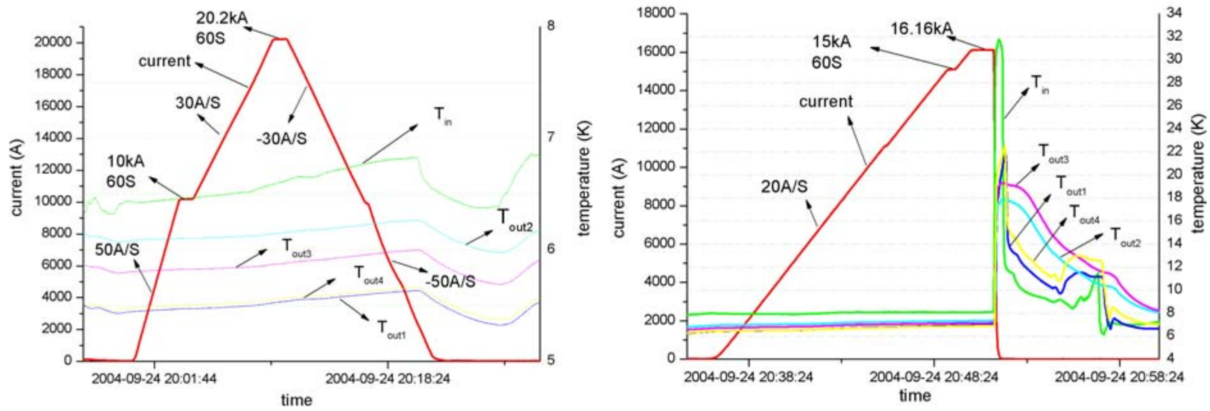
(a) *(b)*

FIG. 3. Test current scenario (a) and quench current test (b) of the CS prototype coil

At the beginning of August of 2004, one set of divertor coil was tested successfully. The coil was charged up to 14.5 kA with 5 T at 5.2 K and much stable even with the varied current of 10 kA/s, 3.45 T/s in 600 ms. The tests of CS and divertor coils gives us much confidence to operate EAST PF system well in the future. The results of high flux in several hundreds milliseconds on superconducting magnets also imply the possibility for realizing the plasma fast control by PF system only, instead of separated control coil system.

In 2003 a prototype TF magnet was cooled down to 5.2 K after 100 h. The superconducting performances, such as nominal current operation and quench current test at different temperatures, were tested. The magnet was quite stable. Following above test, up to Oct. of 2004, fourteen TF magnets have been tested successfully and their superconducting performances are quite similar. Two typical test results of the12th TF coil, which was just finished in the end of September 2004, were shown in FIG. 4. FIG. 4 (a) shows the coil was very stable with 20.2 kA, 4.44 T at 6 K. Its $\vec{B}\times\vec{I}$ is even more than that of the normal operation at 14.3 kA and 5.8 T. The quench current was cached as 16.16 kA at 7.7 K, seeing FIG. 4 (b). Based on above results the extrapolated quench current at 3.8 K with peak field of

6.72 T can be calculated to be 58 kA which indicates I_{op}/I_q is still less than 0.3. It implies there should be possibility to operate the TF magnet system of EAST with higher current if the cryogenic and refrigerator system is updated to reduce the helium temperature to 3.8 K. During the tests of cryogenic and superconducting performances, the stresses on the TF magnet also detected. CICC joint design and fabrication technology have been verified for less than 4×10^{-9} Ω at 18 kA.



(a) *(b)*

FIG. 4. Test current scenario (a) and quench current test (b) of the 12th TF coil

After successful development on the manufacture technologies till the end of 2002, no matter by ASIPP or China industries, manufactures of the main parts of EAST have been processing very well. The main parts of the machine have been delivered to ASIPP in succession from 2003.

The body of the vacuum vessel had been delivered to ASIPP in sections and welded together, but with one section un-weld for the assembly of the VV thermal shield and TF. The VV thermal shield and the CV thermal shield have been fabricated and pre-assembled by a Chinese industry.

Considering the experiences accumulated in ASIPP and the schedule control, some of important subsystems of EAST are also integrated and tested by ASIPP, they are 2 kW/4.5 K cryogenic and refrigerator system, power supply systems of TF, PF and plasma fast control, pumping and fueling systems, water-cooling system, LHCD, ICRH and ECRH systems. Now the water-cooling system is ready for the PF power supply system. The ICRH system with a 1.5 MW (30-110 MHz) generator and liquid stab-tuner of are finished. The pumping and fuelling systems are ready for test. The installation and integration of the cryogenic and refrigerator system will be finished in March of 2005. A 2 MW/2.45 GHz LHCD system is under construction and will be ready on July 2006. The antenna design is now cooperating with Tore-Supra team. The new NBI system design is cooperating with GA and could get ready even more lately.

One set of PF power supply systems had been verified during the test of the prototype CS and TF coils by controlling charge/dump currents at different rates. During the last campaign of the HT-7 operation, the PF magnet system of HT-7 was powered by the same set of the PF power supply system of EAST. It worked and was qualified pretty well. One model system of the EAST data acquisition system is also tested very well with up to 240 s long pulse discharge during last campaign.

The buildings, including a new EAST hall and other appurtenant buildings, have been ready for the EAST assembly, the integration of cryogenic and refrigerator system and the power supply systems. An 83 MVA transformer station with a 110 kV transmission line had been set up and operated normally in 2003.

3. Assembly Plan

The configuration of the superconducting tokamak is much different with conventional one for its additional cryostat with thermal shields. After assembly of superconducting tokamak, the magnet system covered by cryostat is almost inaccessible. For its special constitution and assembly precise, especially for the alignment of the in-vessel components to the magnet system after the machine assembly, a reasonable assembly procedure of the EAST machine with a measurement technique should be defined carefully [4].

Because the main parts of the superconducting machine, such as VV, TF&PF and TS, operate at different temperatures, but are assembled at room temperature. So, the magnet field distributions inside VV should be measured carefully before normal operation. In addition, any helium leakage in the superconducting machine is fatal fault. Even all TF and main PF superconducting coils of EAST are tested cryogenically before installation, to ensure the quality of the superconducting magnet systems and helium cooling system and measure the field distributions, a pre-cooling down process of the machine is planed.

3.1. Survey Control System

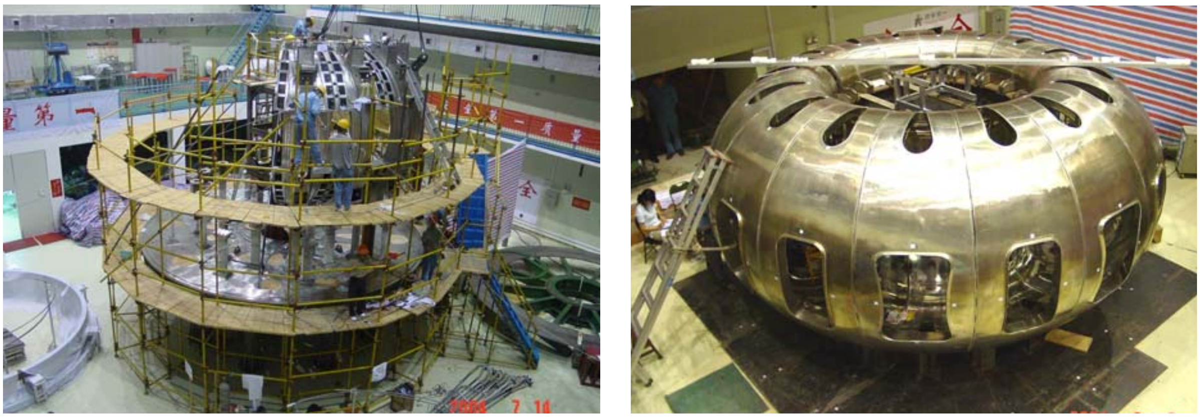
To control position and orientation of the main parts, a survey control network has been set up in the EAST hall. The network is consisted of an orientation survey control network, an altitude survey control network and a digital coordinates survey control network. The most critical specifications of the assembly are alignment precisions of the in-vessel components with the magnet system. Considering the handling weight limitation of the overhead traveling crane inside the EAST hall, it is impossible to adjust the whole TF magnet torus of 200 tons. A conversion coordinates based on the TF assembly axis will be set up after the TF magnet torus is formed. And all other components will be installed and aligned with the axis. Due to the inaccessibility of the magnet systems after the machine assembly, the digital coordinates survey control network is convenient and effective for coordinates transforming between the globe assembly system and the local system of each part. During the engineering design of the EAST machine, not only the assembly datum planes, but also the specified targets on each main part have been defined as the measured datum points.

3.2. Assembly Procedure

The assembly procedure of the EAST machine is mainly constituted of three sub-procedures that are the bases assembly, the tori of VV, vacuum vessel TS and TF assembly and the peripheral assembly. Before the first procedure, four TF magnets have been pre-assembled in advance for getting experiences and finding problems, seeing FIG. 5 (a).

During the bases assembly procedure, the base of CV has been installed on the support platform. A temporary support frame from the centre port of CV was installed, independently with CV, for mounting theodolite or total station and TF temporary support. Following is the installation and position of all supports for VV, the cold mass and TS on the base. Then the base part of TS was installed on its supports. Since three lower PF coils are attached under the TF torus assembly, they will be stored on the base of TS temporarily.

The assembly of tori of VV, vacuum vessel TS and TF could be a time-consuming procedure. On a subassembly platform, the torus of the VV body without ports has been pre-assembled, seeing FIG. 5 (b). Strengthen welds between fifteen sections have been performed, except for the last section of 22.5^{o}. Also, the torus of TS has been pre-assembled to fine and fix problems. The VV torus will be installed on a temporary support with the last section absent. Each section of TF and the vacuum vessel TS body will be inserted from the gap and rotated to their positions. The most difficult assembly is the last TF section subassembly. The last section of the TF pre-assembled with one section of VV and TS inside has to be inserted into the gap left before. The section of the vacuum vessel inside is divided into two smaller parts for having space to connect TS sections with its neighbour. After three tori are formed and adjusted to right positions, the last VV section will be welded with others inside VV.



(a) *(b)*

FIG. 5. Pre-assembly of four TF coils (a) and the body of VV (b)

The peripheral assembly will begin with three lower PF coils installation. Other three upper PF coils will be lowered from the top of the TF assembly down to the position. The subassembly of CS will be finished on a subassembly platform in advance and hanged into the hole formed by wedged straight legs of the TF cases. Before next procedure, the treatment of joints of conductor, cooling channels and manifold must be finished. The middle ring and the top of the cryostat vessel TS will be installed to position and cover all the cold mass of 4.5 K. All duct shields of VV will be inserted from the outside of TS. The cylindrical section and the cap of CV will be installed in the same way as the cryostat vessel TS. All the sensors inside the machine for the diagnostics of stress and strain, temperature, shortcut between two main parts, quench detection and fluid measurement should be installed properly.

3.3. Pre-test of the Machine and the Final Assembly

Up to the end point of above section, it could be easier to disassemble the machine in principle because of without the VV ducts welded on. But the machine is ready for pumping and cooling down with blank flanges covering all CV ports. So, after the peripheral assembly procedure, the machine will be vacuum pumped. And superconducting magnets will be cooled down and then charged and tested. During the test of the magnets and cooling system, the distribution of the magnet fields inside VV will be measured carefully. After the superconducting magnet systems and the cryogenic system are qualified, all ducts of VV will be inserted into their corresponding shield ports of TS from the outside of CV and welded with the collars on the VV body inside VV. Then the in-vessel components for the initial operation will be installed.

4. Operation Plan in the Future

The first plasma hopefully could be got in 2005. The operation plan of EAST will be in principle consisted of three phases [5]. Based on the experience on the HT-7 superconducting tokamak, the first phase, that is commissioning phase, could be less than two years. During the first phase different plasma configurations, including circle cross-section at first and then divertor configurations will be tried mainly by basic ohmic heating combining with total 3.5 MW non-inductive current drive and heating from short to longer discharge. In the second phase of about ten years, additional 8 MW of non-inductive current drive and heating including 4 MW NBI will be put into the machine. Different advanced operation modes with divertor configurations will be tested under long pulse or even stead state conditions. In the third phase, the TF system may be charged up to 4.0 T at the major radio of 1.7 m with update of the cryogenic and refrigerator system to reduce the helium temperature to 3.8 K. As a consequence the plasma performances, especially the β, may be increased. Eventually EAST will have more than 23 MW non-inductive current drive and heating power.

5. Summary

The key R&D program on the engineering and physics of EAST has been successful. The significant progresses, especially on the fabrication and test of all TF and PF superconducting magnets, have been achieved during last two years. The assembly of the machine has begun. A pre-test procedure during the assembly for ensuring the quality of the superconducting magnet systems and the cooling system will be performed in the early of 2005. The first plasma hopefully may be got around end of 2005. EAST will open to the fusion research society not only domestically, but also internationally.

Acknowledgment

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