Risk Analyses and Optimization of Safe Operation for Advanced Superconducting Tokamak

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1. Introduction

1.1. Fusion reactor should be steady state operation (SSO)

As everyone known the significant progresses have been achieved on tokamaks, which means that the scientific feasibility of tokamak reactor for fusion energy has been achieved (Q=1). But for commercial power plan the economics will be very important. Therefore to find improved (advanced) confinement operation model is the popular topic always for tokamak research. On other hand if any tokamak only can be pulse operation the averaged efficient with the time will be very low for any advanced models. Therefore the steady state operation (SSO) will be the most important issue and it should be the fundamental requirement for the future fusion reactor.

1.2. Superconducting tokamak (SCT) is one of the most important bases of SSO

Three basic conditions at least must be required for SSO of Tokamak: 1) steady state toroidal field (TF); 2) steady state polodial field (PF) for shaping and equilibrium; 3) the plasma current should be sustained by non-induced current drive (CD). The SC magnet can be used for TF magnet on tokamak has been demonstrated on T-7 (HT-7), Triam-1M, Tore-Supra. The CD by LHCD, ECCD, NBCD, ICRFCD and bootstrap current has also been demonstrated on tokamaks. But there is no the full superconducting Tokamak until 2006, for which both TF and PF magnet are SC. The full superconducting tokamak is the most important bases of the SSO fusion reactor. For the full superconducting tokamak the PF magnets will suffer high voltage and AC loss which is related with the fast flux change during start up, ramp up and the disruption of plasma current and the instability control. The high voltage and AC loss will cause quench or arc discharges inside cryostat. It can damage the PF system and, even more, the whole tokamak device. So design, construction and operation of the **full** SC tokamak will face more big challenges than the tradition tokamak and even the SC tokamak, on which only TF is SC magnet.

1.3. ITER, EAST and KSTAR

ITER (International Thermonuclear Experimental Reactor) should demonstrate SSO with the burning plasma. So both PF and TF of ITER have to be SC magnet and that is why the ITER will face to great challenges related with both burning plasma and full SC magnets. Before ITER to be constructed the EAST (Experimental Advanced Superconducting Tokamak) in China and the KSTAR in Korea have been built successfully and the first plasma have been obtained in 2006, 2008 respectively. Both EAST and KSTAR are the full superconducting tokamak with the elongated divertor configuration (advanced configuration). They will certainly make important contribution to SSO of ITER and future tokamak reactor both on technology and physic.

2. Risk analyze for Advanced Superconducting Tokamak (ASCT)

2.1. Special points of the full SC tokamak

Big differences between tradition tokamak and full SC tokamk are: 1) all magnets for ASCT are superconducting magnet. They must work stably at the very low temperature condition (for example 3.8-4.5 K). 2) In order to significant decrease the heat load any SC tokamak must have the second vacuum chamber cryostat. 3) Inside the cryostat there are thermo-shields, TF and PF magnets and very complicated support systems worked on different temperature ranges. 4) Inside the cryostat there are hundreds of cooling pipes which will provide liquid helium for magnets and support system. The pipes must be insulated very well with magnets. They also should be welded and supported careful. Otherwise they will suffer large thermal stress when the temperature decreased from room temperature to the liquid helium temperature.

2.2. Risk analyze

For the SC tokamaks such as HT-7, Triam-1M, Tore-Supra, only TF magnets are SC. The major risk for them dependents on the quality of quench protection system. The system should be very sensitive and can quickly switch to protection circuits to move the storage energy inside TF system out as soon as possible with suitable induced voltage when quench happened. But for the full superconducting tokamak all PF magnets are SC and they are located in the cryostat. There are very strong coupling between PF coils and plasma current. The currents on PF magnets, in general, are required to be rapid change in order to induce the loop voltage for start up, ramp-up and feedback control of plasma current, also in order to control the shaping, eguilibrium and instability. By all kind of rapid current changes including the plasma current disruption the PF system will suffer AC loss and high voltage. The fast flux change by current change also will cause very complicated electric-magnetic forces on many components inside cryostat such as cooling pipes, insulators, support systems and so on. If there are any damages on cooling pipes or insulators it will cause helium leakage. The leak will decrease the vacuum performance of cryostat and then the cryostat will be the second discharge chamber. The damages some time can feedback together with high induced voltage to cause the quick development of serious arc discharges which will possible damage the whole PF or TF system and, even more, the whole tokamak device. We have suffered this kind of damage during the component test on our cold coil test facility.

Therefore the risks during manufacture, assembly and operation for the advanced full superconducting tokamak such as EAST, KSTAR and ITER will be much high than the tradition tokamak. It is because:

- The vacuum vessel is plasma discharge chamber. The cryostat could be second discharge chamber if the vacuum performance is poor and the voltage on any PF coils is too high.
- All PF coils will suffer high voltage and AC loss caused by fast flux changes (start up, ramp up, disruption of plasma current; feedback control by the current change on PF coils, which can cause the insulation broken and quench of PF system.
- Any leakages of insulator or pipes inside cryostat will increase heat load of whole system and decrease the quality of all insulation which will result arc or discharges in cryostat and will cause serious damages of coil systems. The internal leakage is terrible because it is difficult to be fined and the leaked gas is helium which is difficult to move out from cryostat by pumping.
- The sub-cryostat of current leads is the most danger system where the highest voltage on PF current leads can cause the serious arc discharges if vacuum and insulation are poor.
- The quench protection for each PF magnet should be decoupling with all other PF magnets carefully. Otherwise the quench protection can make many mistakes to cause unreal quench protection which will shorten live time of PF and maybe the real quench cannot get the protection on time

ITER will demonstrate SSO for the burning plasma with the advanced magnetic configuration and it will face to great challenges related with both burning plasma and full SC magnet systems.

3. **EAST project** [1].

3.1. Mission of EAST

EAST is an Experimental Advanced Superconducting Tokamak and it was approved as the National Mega-Projects of Science Research (MPSR) by Chinese government in 1997. The main parameters [1] are B_T=3.5 T, R_0= 1.70m, I_p=1MA, a= 0.4m, (b/a) = 1~2 with the flexibility of double and single null divertor configuration. At the first phase P_{LHCD}= 3.5 ~ 4 MW, P_{ICRH}= 3 ~ 4 MW, P_{ECRH}= 0.5MW and the maximum pulse will be 1000 seconds. In the second phase B_T = 4.0 T and I_p = 1.5MA will be achieved if the working temperature on magnets can decrease from 4.2 K to 3.8 K.

The mission of EAST is to widely investigate the physics and technology of the SSO advanced tokamak as well as the power and particle handle under SSO condition. The basic requirements for EAST tokamak are: both TF and PF should be SC magnets; enough inductive current system for plasma start up; CW non-inductive current drive (CD) and addition heating systems for SSO; the flexible control of J(r), P(r), plasma position and shaping for advanced tokamak research; the standard PFC with changeable tiles for advanced first wall material development; the divertor for power and particle handle; advanced diagnostics.

3.2. Progress of EAST

3.2.1. Successful manufacture of EAST [2]

The significant progress of EAST during the manufacture has been achieved [2]: Special CICC (cable in conduit conductor), all TF and PF magnets, some key components such as joint, high Tc current leads, insulators were fabricated and produced by CASIPP with the good quality; The final assembly completed successful at the end of 2005 and then the first and second engineering commissioning were very success at early of 2006 (Fig. 1, 2). All engineering design parameters such as B_T, flux change ability, cryogenic ability have been achieved and all sub-systems can be safely operation and satisfy the experimental requirements. All these mean that the quality control during the manufacture and final assembly are very success.

3.2.2. Successful operation of EAST[3,4]

Even if there are more operation risks for ASCT the significant progress of operation of EAST has been achieved. Three experimental campaigns have been down safely and successfully since 2006. In the first campaign the first plasma has been obtained in Sept.26, 2006 (Fig 3). In the second campaign both single and double null divertor configuration plasma with elongation K~1.7- 2 have been achieved (Fig.4). In third experimental campaign the elongated single null and double null divertor discharges with higher plasma performance have been obtained (Fig. 6) after the fist wall material was changed from stainless steel to the graphite as well as the active cooling and divertor pumping system. The plasma currents have achieved the range of 500~800 KA and the pulse long has achieved about 20 second with 2MW LHCD and 2MW ICRF.

3.3. Quality control and operation optimization of EAST

All above achievements are based on the successful quality control during the manufacture and the optimization of design and operation model as following:

1) Very good quality control during the manufacture for any components especially

for CICC conductor, insulator, winding of coils, sub-assembly of the thermal shields and so on. For example the any insulator must be tested by thermal cycles (room to liquid N_2 temperature quickly) more than 20 times and then do leak and insulation tests by high pressure and high voltage. Otherwise the components can not be used for final assembly. Also during the manufacture of CICC six independent measurements to check the weld quality have been adopted seriously. Before the winding each of the whole pieces of CICC conductor must be passed the leakage test in a vacuum chamber with high pressure inside the pipe of CICC.

2) The cold coil tests for all PF and TF magnets have been down successfully (Fig.5). The tests are checking leakage, rated working current, and resistivity of internal current joint under the low temperature condition. Under this condition the quench tests for all TF magnets have been down to predict the real performance of each TF magnet under the real operation condition (high background magnetic field). Due to the full success of the quality control during the manufacture, in fact, no any quality problems of magnets were found by the cold coil test but the design performances and parameters on conductor and magnet have been proved directly or indirectly by the tests.

3) Because many welds between insulator and pipe, many joints and support systems should be down on site during the final assembly and no way to do cold test. Therefore the quality control at this stage is more difficulty but the most important even if the quality controls during the manufacture already are very success according to our experiences. If there are some quality problems which was not found during the final assembly it maybe can not be found for ever until the engineering commissioning. But it is too late. As long as it is found during the commissioning the tokamak device maybe should be totally disassembly. So during the final assembly the leak test with high pressure for each of welded points must be down even if it is very slowly and very difficulty. Also the insulation quality should be checked every day and make the necessary record. The joints between magnets which can not be tested by the cold test must be assembly on site by the well- trained excellent skilled worker.

4) Even if the quality control during fabrication and assembly is good the full SC tokamak will still face to the big challenges during the operation which is mainly caused by high voltage and AC loss on PF magnets. Right design and optimization of the operation scenarios will be very important to decrease the operation risks. For example EAST choose a full metal vessel with double wall and no electric gaps as the vacuum vessel, which is similar to ITER design. The vessel is a shielding shell and it’s time constant is around 10-20 ms. The induced voltage on large PF coils by disruption can be significant decreased by more than five times, which has been proved by both design calculation and experiments. But on the other hand the full metal vacuum vessel will shield the feedback control effect given by PF coils which is located outside the vessel. If the PF coils are only coil system to be used as the instability feedback control coils the power supply will be required more powerful by higher voltage. As the result the AC loss and the heat load on the PF coils will significantly increase. In general for safety the

in-vessel coils for instability control on ASCT is necessary. EAST has this kind of coils.

5) It has been required for safe operation on EAST: carefully control the breakdown voltage as below as possible; the vacuum of cryostat and sub-cryostat of current leads should be always below the 5×10-5 Pa; the in-vessel coils must be used for instability feedback control especially for the SSO with elongated divertor configuration operation. In this case the value of averaged dB/dt on PF coils should below 500A/S which will cause AC loss and temperature increase but less than 0.5 K according to our experiments on EAST (Fig.7). Otherwise the quench can happen if the current on PF coils is high.

4. Further possible optimization for safe operation of ASCT

The goal to build ASCT is going to SSO of the future advanced tokamak reactor. The current on PF coils can divide into three parts by the different roles: transformer current, the current for shaping and equilibrium and the current for instability feedback control (usually it is AC current). On the present tokamak the role of transformer current is initiate, ramp-up and then to sustain the plasma current as longer as possible. For this purpose usually the transformer current on PF coils, especially on the centre-solenoids should be developed from the positive maximum value to the negative maximum. For SSO the transformer current on the stage of sustain plasma current can not be used to keep the plasma current as longer as you like. Otherwise the current on the PF coils will too large which will cause quench certainly because the current on PF coils can not infinitely increase or decrease. For SSO the plasma current should be sustained by induced CD in almost all time. If we still use the transformer current for initiate, ramp-up and sustain the plasma current on ASCT it should be noted that keep the maximum on PF coils especially on centre-solenoids for SSO will be increase the quench opportunity and cause risks. The future optimized safe operation scenarios should be to as early as possible to start induced CD to save the flux change which caused by transformer current change. In the best situation all transformer current on PF coils should change from positive maximum value to the zero and then the plasma current should be sustained totally by induced CD such as ECCD, LHCD, NBCD and bootstrap currents.

Summary:

There are very high risks during both manufacture and operation for advanced superconducting tokamak :

Any helium leaks inside cryostat will increase heat load which can cause all or part of magnets can not be into the superconducting state. If it happened it will be very serious because the tokamak could be required disassembly totally in the most of situation and then reassembly;

The cryostat is possible to be a second discharge chamber and all PF coils for ASCT are located inside the cryostat. In consequence all components inside cryostat, especially the PF coils for ASCT will suffer high voltage, AC loss and electric–magnetic forces which can easily cause leakage. If some arc discharge is happened inside the cryostat by quench, or by high voltage, or AC loss tokamak will be seriously damage which is also possibly need to disassembly for maintain and then reassembly;

By the success of quality control and optimization of the operation model EAST has begun the normal experimental operation since 2006. Important progresses on first plasma, elongated double or single divertor discharges with 500-800 KA plasma current and about 20 seconds pulse long have achieved. The more optimization operation scenarios with high performance plasma for safe operation will develop further, which can make more useful contributions to ITER certainly.

Reference:

[1] EAST Team, 'Design of the EAST (HT-7U)' October 2003, Hefei, China
[2] Y. X. Wan et al "First Engineering Commissioning of EAST Tokamak", Plasma Science and Technology Vol.8, No 3, May 2006,
[3] Y. X. Wan et al "Overview Progress and Future Plan of the EAST project" OV/1-1 on 21th IAEA FE Conference, Chendu 2006, China
[4] B. Wan for EAST team**…** "Physical Engineering Test and First Divertor Plasma Configuration in EAST" Plasma Science and Technology Vol.9, No2, Apr. 2007;

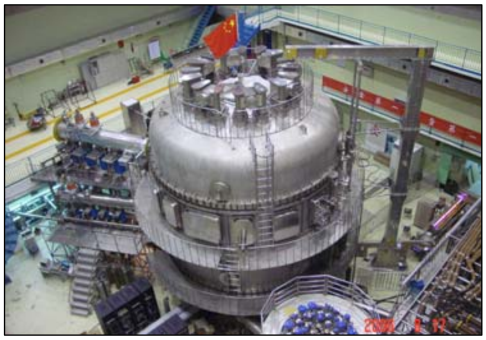

Fig 1 EAST

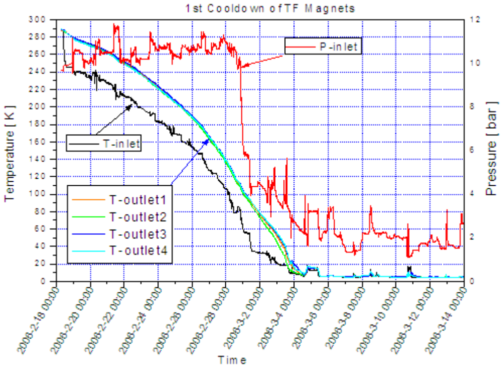

Fig 2 The first commissioning

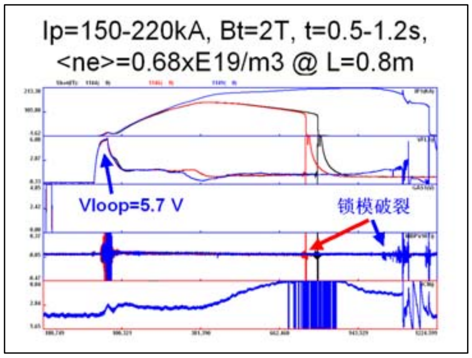

Fig. 3 The first plasma of EAST

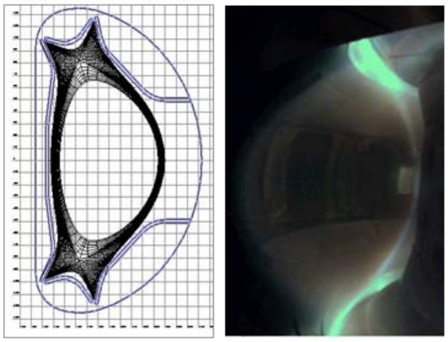

Fig. 4 The first divertor plasma

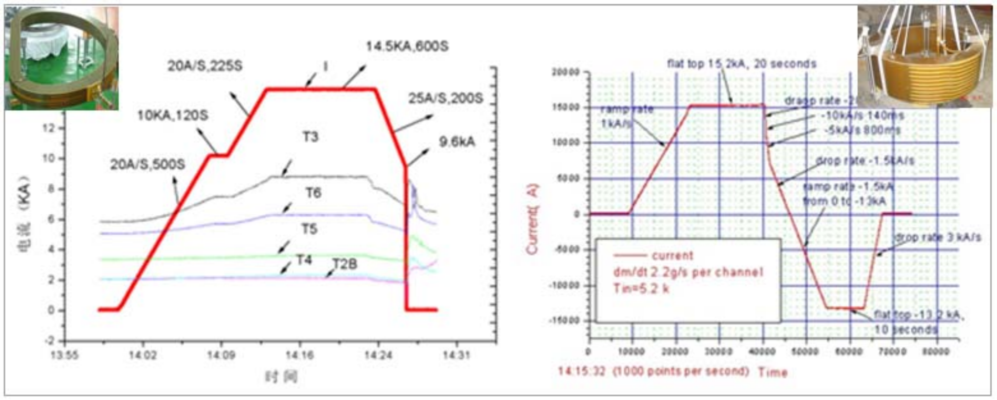

Fig. 5 The cold tests for all TF and PF magnets have been down successful

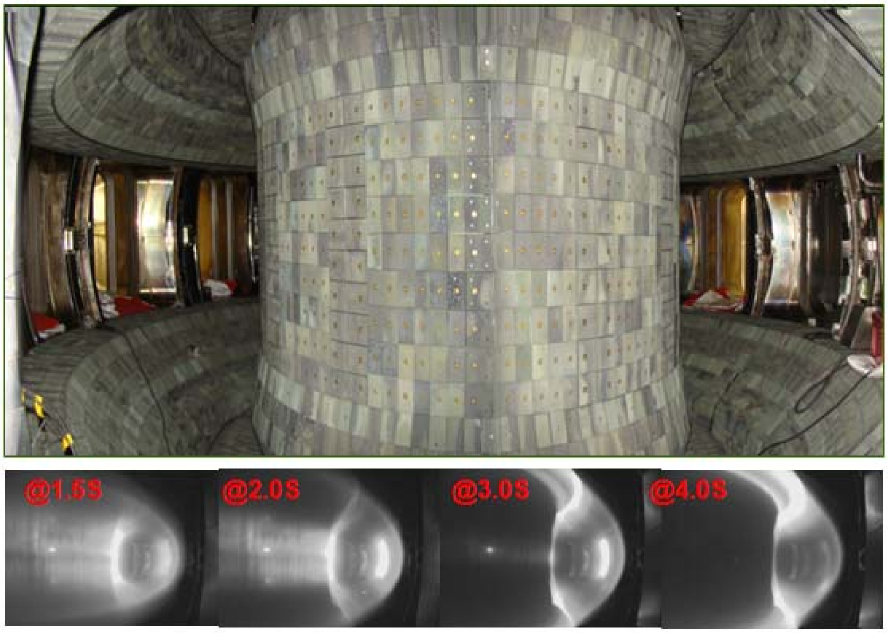

Fig. 6 The elongated divetor discharges have been obtained with full graphite first wall I_P is at the range 500~ 800 kA and pulse long can be ~ 20 S

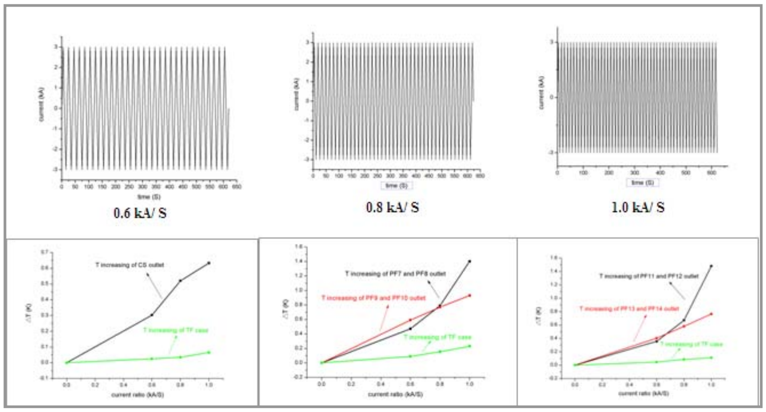

Fig. 7 The temperature increase on PF coils and TF case by AC loss by different dI/dt