PIONEERING SUPERCONDUCTING MAGNETS IN LARGE TOKAMAKS: EVALUATION AFTER 16 YEARS OF OPERATING EXPERIENCE IN TORE SUPRA

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Abstract

The toroidal field (TF) system of TORE SUPRA (TS) is superconducting. After 16 years of operation it is possible to give an overview of the experience gained on a large superconducting system integrated in a large Tokamak.

Quantitative data will be given, about the TF system for the cryogenic system and for the magnet system as well, concerning the number of plasmas shots and the availability of the machine.

The origin and the number of breakdowns or incidents will be described, with emphasis on cryogenics, to document repairs and changes on the system components.

As concerns the behaviour during operation, the Fast Safety Discharges (FSD) in operation are of particular interest for the Tokamak operation, as they interrupt it on a significant time of the order of one hour. This aspect is particularly documented.

The approach followed to decrease the number of these FSD will be reported and explained.

The TORE SUPRA Tokamak was the first important meeting between Superconductivity and Plasma Physics on a large scale. Overall, despite the differences in design and size, the accumulated experience over 16 years of operation is a useful tool to prepare the manufacture and the operation of the ITER magnets.

1. Introduction

The acceptance tests of the eighteen coils plus one prototype of the TF system of TS took place at CEA Saclay in 1986-1987. In 1988 after the first plasmas at reduced TF current, the BT17 coil was damaged due to an arc initiated by a short circuit and had to be replaced. The design of the coils is based on bare conductors immersed in superfluid helium and taken in a double system of steel casings (see Figures 1a and 1b). This concept improves the capability of the coils to absorb energy perturbations but makes them particularly sensitive to short circuits. To take into account this weakness, the fast safety discharge concept was completely changed and the voltage across the coil terminals during this phase was reduced from 3500 V to a value under 500 V [1], [2].

2. Status of the TORE SUPRA toroidal field system

2.1 Critical current and margins on the TF system of TS.

On the TS coils, the operating point was chosen such as to absorb perturbations and plasma current disruptions. As visible in Figure 2, on the load line the critical current is reached at 4.2K, for the nominal TS values (1400 A and 9 T). Thus the margin is 2.4 K for an operation at 1.8 K.

In 1989, the replacement of BT17 by BT19 had some consequences on the TF current. The BT19 was a prototype coil made with an early version of the strand and the Ic curves of Figure 2 are slightly shifted towards the left. To keep the same margin, the TF current had therefore to be limited to 1350 A.

2.2 Default on BT13

Till 1995, a particular behaviour was observed during FSD on coil BT13. During the acceptance tests of the system in 1989, this coil quenched during the triggered FSD from 1450 A. The current operation was then limited to 1250 A and the temperature increase during FSD was higher in this coil than in all the other coils. The reason for this behaviour was probably of the same origin as for BT17, but in this case the short circuit affected only a turn and not a full pancake. A model based on calorimetric measurement made in superfluid helium was presented in [3]. From 1995, after a thermal cycling between low temperature and room temperature associated with a shut down, this manifestation disappeared and the BT13 coil does not present any more a particular temperature increase as visible in Figure 7.

3. Normal operation in TS

3.1 Statistics

Thermal cycling: 13 thermal cycling were performed between room temperature and 1.8 K (13 thermal cycling between 1.8 K and room temperature)

TF Current cycling: along the operation, the following number of current cycles were performed:

609 up to a current between 0 A and 600 A, 179 up to a current between 600 A and 900 A,

490 up to a current between 900 A and 1200 A, 735 up to a current greater than 1200 A

Plasma discharges: 20074 plasma discharges have been performed.

3.2 Impact of normal operation on cryogenics

3.2.1 One day of operation

A particular day has been chosen to show the impact of plasma operation on cryogenics. This day was the 4 th of December 2003 when, in particular, two six minute long plasma discharges were performed with 1 GJ energy injected in the plasma.

In Figure 3 and in Figure 4 are presented the impacts of plasma operation respectively on the temperature of coil BT15 and of the thick casing helium temperature. BT15 coil is representative of the behaviour of the 18 coils of TS.

The effect of plasma operation in coils is due to the hysteretic and coupling losses which are induced in the TF conductor due the associated field variations. These field variations induced also eddy current and heat dissipation in the coils thick casings (see Figure 1 b) which are cooled by supercritical helium circulation in channels.

At the beginning of the day, the impact of the TF current increase is visible, giving 0.06 K of temperature increase in BT15 mainly due to hysteretic losses, the normal temperature operation is recovered within half an hour.

Cleaning discharges to condition the vacuum chamber after a disruption produce a typical temperature increase of 0.25 K in thick casing needing about half an hour for the system to recover. The rest of the operation has little impact on the cryogenics. Heat dissipation is always in relation with plasma initiation but the associated temperature increases are small, less than 0.01 K for the coil temperatures and about 0.08 K for the thick casing helium temperature. Note that the two last plasma discharges of the day which are the 1 GJ discharges had no particular impact on the cryogenics.

3.2.2 effect of a disruption

To illustrate this point, a very severe disruption was selected which occurred on the 18 th of September 2003 (plasma discharge number 31828) from a 1.7 MA plasma current. The plasma current evolution is presented in Figure 5. The corresponding temperature increases are presented in Figure 6 giving respectively 0.83 K for the thick casing helium temperature, and 0.02 K for the coil temperature.

The time needed to recover is linked to the cooling circuit of the thick casing and is about 500 s.

4. Fast safety discharges in the TF system of TS

During the acceptance tests, only one quench of the system occurred on the BT13 coil. Then, during the whole operation of the system, only one quench occurred in 1989 on BT04 coil after a very severe disruption of the plasma current. However the system suffers every year from several FSD (Table 1) which are not associated to a quench of any coil. A lot of attention was devoted all along these 16 years to decrease the number of these FSD.

FSD is the only case when an important voltage exists across the coils (320 V corresponding to 1400 A). This voltage is low but this event has to be avoided as much as possible. The weak point of the system is the presence of bare conductors and the associated possibility of short circuits. In addition, the FSD induces a thermal load on the system which needs some time to recover and the operation is correspondingly interrupted. As visible in Figure 7 the impact on the cryogenic system is large. The temperature increase in coils is typically of 0.37 K with a very similar behaviour in the different coils. The apparent higher temperature of BT13 is due to a problem of sensor calibration, as visible on the values of the temperatures before the discharge. The temperature increase of the thick casing helium circuit is about 1.6 K. The time needed to recover is about 2h30. This long time is due to the fact it is very difficult in real time to discriminate whether the FSD is associated with a real quench (which never happens in practice) or not. For this reason the cryogenic system adopts a configuration for the worse case i.e. the quench, and triggers heavy actions to protect itself such as the bypass of the thick casing helium circuit and the stop of the pumping on the HeII saturated bath.

An examination of the origin of FSD (Table 2) shows that many of them are due to the neutral injection beam (IDN) or to the ω_{ci} wave (FCI). For the other cases they may be preceded by secondary alarms triggering a decrease of the current, the fast discharge is therefore started from a lower current. To mitigate the perturbation on the Tokamak operation an important effort was devoted to make the protection system of TS magnets more insensitive to electrical perturbations. It was done by using time delays on alarms as long as possible [2] without affecting the protection of the coils in case of a real quench. An important effort has been made in sensors conditioning.

The source of perturbations has been reduced as much as possible by properly grounding the electrical circuits. In addition, in 2003, a control system was developed which can shut down the source of interference emission before the initiation of a FSD.

5. The cryogenic system of TORE SUPRA

Detailed information about the cryogenic system of TORE SUPRA can be found in [4], [5] [6]. Concerning the magnet operation itself, little manpower is needed and limited to checking procedures after every cool-down from 300 K, and fault event analysis in case of incident operation such as FSD. Some work has been performed to make the discharge safety system more insensitive to electrical perturbations during plasma operation.

The cryogenic system operation is much more different: it is operated twenty four hours a day and seven days a week, during typically 9 months per year, by a team of 12 people, thanks to a fully automatic control system. The cold powers required at different temperature levels, for each operation mode of the cryogenic refrigerator, are presented in Table 3. The total electrical consumption is given for the different modes. In normal operation the nitrogen consumption is typically of 6000 l/day. The helium consumption rises up to 12000 l/year due to imperfect tightness of the system and also to users external to TS.

The total yearly maintenance cost including the refurbishments, the helium and nitrogen consumption, but excluding the energy and the staff cost, is in the range of 0.5 M€.

5.1 Major concerns experimented during routine long-term operation

Electro mechanical concerns:

Some incidents linked to the very short life span of the **compressor motors bearings** have led to install vibration measurement for all the bearings. The lubrication period set by the constructor is varied as a function of the indications given by the vibration analysis.

Corrosion on water cooled **black steel exchangers** in the compressor house required changing all of them with stainless steel ones.

After a shut down of the cryogenic system and the consecutive opening of the **safety valves** protecting the cold circuits from overpressure, these valves were no longer tight due to the cold helium discharge. To mitigate these leaks, two solutions have been implemented:

- All the safety valves protecting the cold parts were duplicated and a three-way valve system allows the change over from one valve to another.
- On pressurized cold circuits, pressure-controlled cryogenic valves were added in order to avoid unnecessary opening of the safety valves.

Cryogenic components concerns:

Thermal losses from the 4.5 K circuits due to the excessive gas content within the helium used for supplying the electrical current lead connection cryostats: a large part of these losses have been suppressed by adding a phase separator which supplies the current lead cryostats with pure liquid helium.

Pollution of 80 K shields circuit. The 80 K shields cooling helium was not purified and caused partial clogging due to frozen CO and CO2 impurities. These circuits were modified in order to fix that problem by purifying all the 80 K flow with active charcoal filters.

A low pressure **exchanger failure** was observed after 10 years of operation. This heat exchanger is used to warm up gaseous helium pumped from the He II saturated bath from 80 K to 300 K. Many thermal cycles carried out over the years, weakened the gripping forces and the thermal contact between the plates of the exchanger and decreased its efficiency.

A tightness breaking of **aluminium / stainless steel junction** of the thick casings circuit appeared after a malfunction of the electrical heater during a warm up to 300 K. An overheating caused an helium leak on this junction into a cryoline. The insulating vacuum of the cryoline was significantly damaged and this junction has been removed during the following maintenance period.

Major gaseous **helium leaks** led to the installation of a recorded helium leak detection system all around the plant and at the external users' laboratories.

The 4.2K thick casing of the superconducting magnet is, because of its large area, a powerful cryopump for hydrogen from the stainless steel walls. After long periods of operation, **high quantities of hydrogen** are cryopumped and if any problem occurs on the cryoplant, the 4.2K thick casing temperature increases and releases H_2. The pumping system has to be dimensioned such as to face this situation. The refrigerator is not adapted to absorb the very large heat load resulting from such a vacuum deterioration.

5.2 The major tendency of the cryoplant ageing.

Although the preventive maintenance of the compressor units gives a good availability of the refrigerator, after 16 years of operation we can identify the major following tendencies for the cryoplant ageing :

- a loss of electrical insulation of many temperature sensors located in the depth of the cryostats.
- a drift of adjustment of the electronic components dedicated to the magnetic bearings of the cold compressors.

- air leaks in the cryostat vacuum vessel due to the tightness seal ageing.

5.3 The global toroidal field system availability

A typical operation year span is divided into three parts, depending on the magnet temperature: the first one (3 months duration) at 300 K or 77 K is devoted to maintenance activities, the second is the magnet cool down and cool up operation (total duration of 6 weeks), and the third part (7.5 months duration) includes the plasma operation at 1.8 K and the idle operation at 4.5 K or 2.2 K.

The global availability of the toroidal field system includes the magnet and the cryogenic system. It is evaluated with respect to the yearly effective plasma operation time (magnet at 1.8 K), and takes in account every event which leads to a plasma operation delay. Over the last two years of TS plasma operation, the toroidal field system availability reaches respectively 92 % and 97 % for 2002 and 2003 which are typical. The reduced availability in 2002 (Figure 8) in comparison with 2003, was mainly linked to the process control which was renovated in 2001. Other sources of non availability are the magnet safety system (electromagnetic perturbation sensitivity) and the associated recovery delay of the FSD, and also some troubles on the He II cold compressors.

6. Conclusion

The TORE SUPRA Tokamak was the first important meeting between Superconductivity and Plasma Physics on a large scale. This experience has demonstrated that superconducting magnets can be operated successfully on the long term with plasma physics. Far from being a burden, the continuous operation of the TF system is a simplification in the preparation of the plasma discharges. No significant heat load is associated to long shots. The non pulsed operation of this large magnet system is also an advantage as concerns the mechanics. Overall, despite the differences in design and size, the accumulated experience over 16 years of operation is certainly a useful tool to prepare the manufacture and the operation of the ITER magnets.

Table 1 Number of FSD per operation year of TORE SUPRA

Operation year	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2001	2002	2003
Number of Fast discharges	1	10	7	6	2	6	5	7	4	7	4	4	9	2

Table 2 Origin of fast discharges on TORE SUPRA TF system

Operation year	quench	Not identified	Refrigeration system	Interference IDN	Interference FCI	Magnet Power supply	Operating system	Detection system
1994	0	0	2	0	3	0	0	1
1995	0	0	1	2	0	1	0	1
1996	0	0	0	0	2	0	0	5
1997	0	0	3	0	0	1	0	0
1998	0	0	1	0	0	0	2	4
1999	0	0	2	0	0	1	0	1
2001	0	0	3	1	0	0	1	0
2002	0	2	1	4	1	2	0	0
2003	0	0	0	2	0	0	0	0

Table 3 Power associated to operation modes

	77 K Power (6000 l of N_2 /day)	4.5 K Power	1.8 K Power	Total electrical consumption
Magnet operation day	10 kW	900 W	300 W	1100 kW
Nights between operation days	10 kW	700 W	0	900 kW
Weeks ends	10 kW	700W	0	900 kW
One week shut down	10 kW	0	0	300 kW

J.L Duchateau Figure 1a

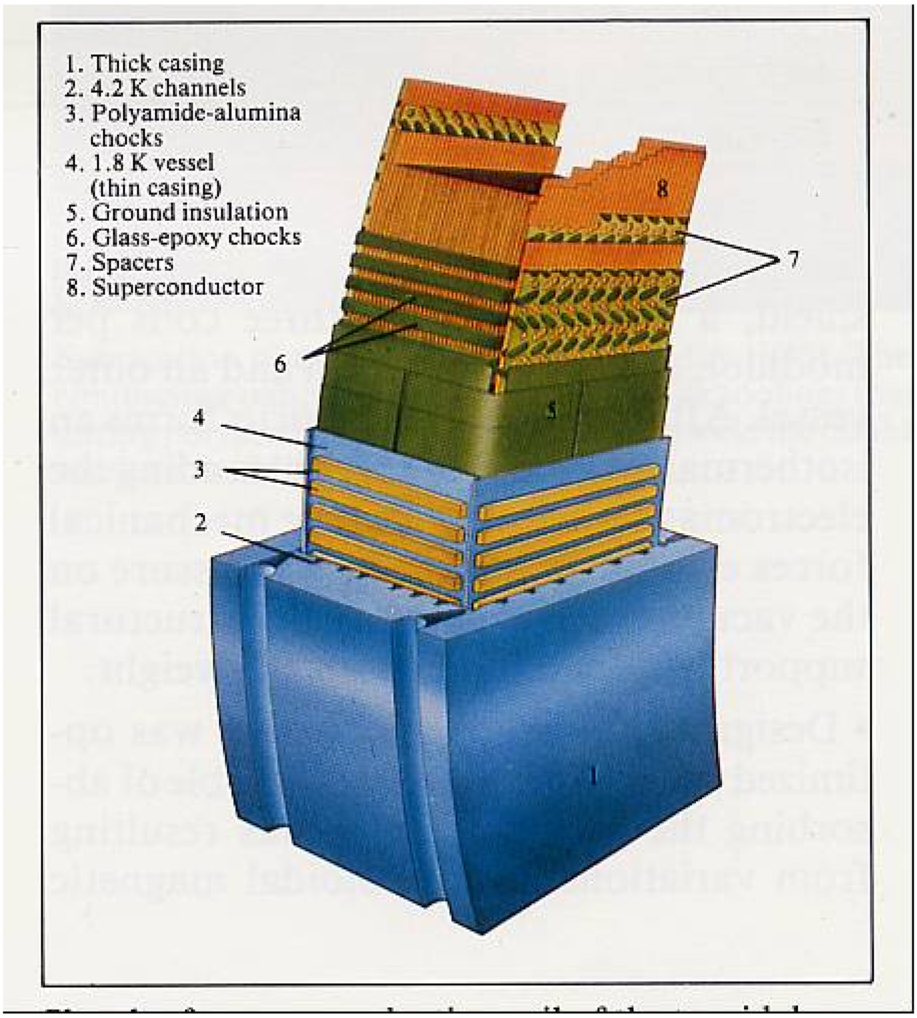


Figure 1a : Sketch of one TF coil of TS showing the bare conductors immersed in superfluid helium confined in a thin casing.

J.L Duchateau Figure 1b

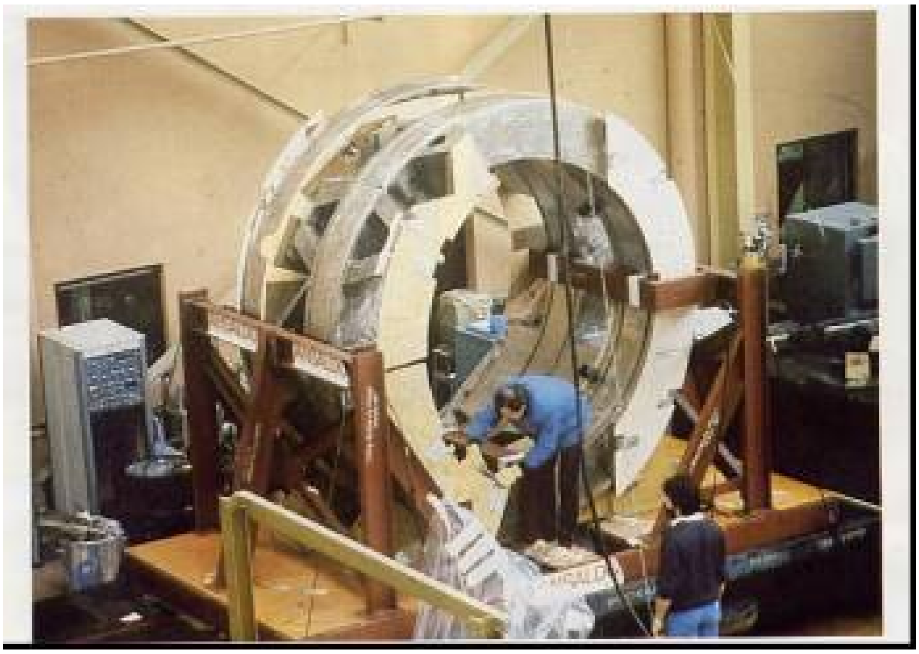


Figure 1b: two of the 18 coils of TS during mounting

J.L Duchateau Figure 2

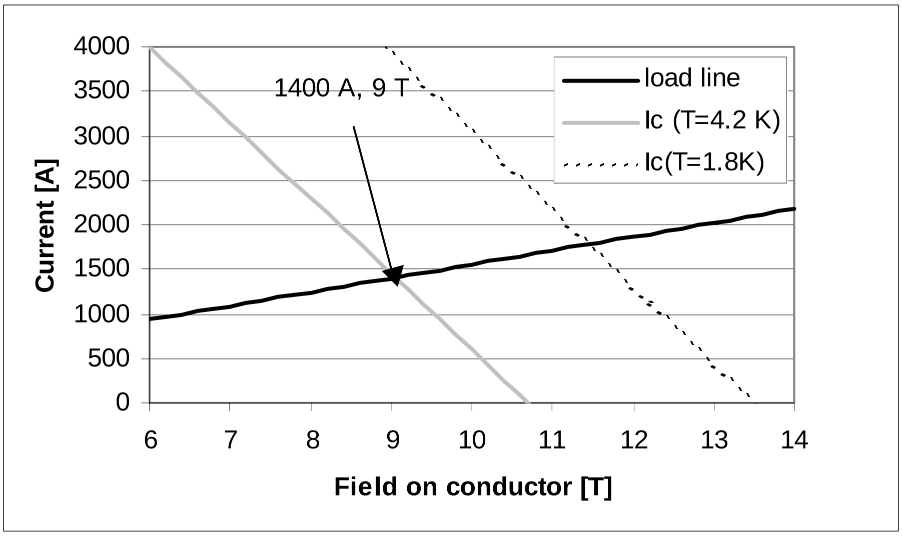


Figure 2: Temperature margin on the TF system of TS on all the coils except BT19.

J.L Duchateau Figure 3

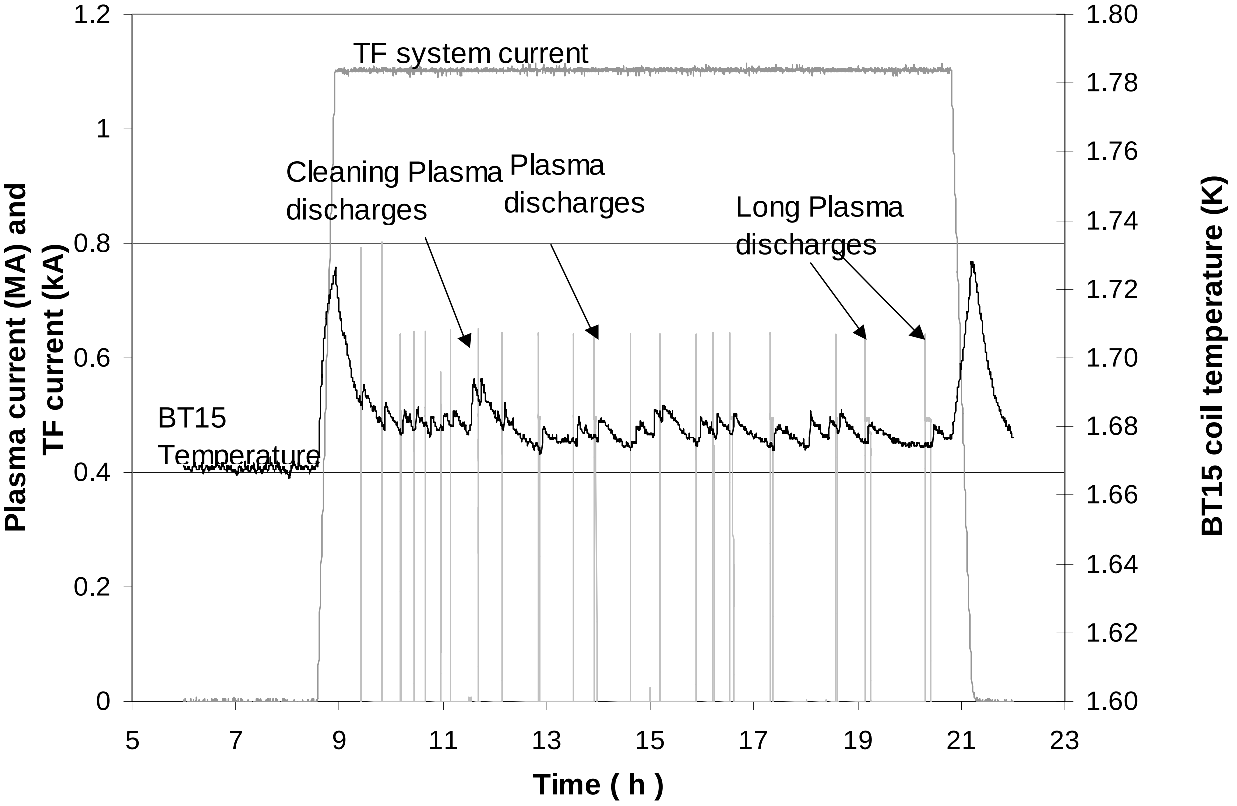


Figure 3: BT15 temperature during one day of operation

J.L Duchateau Figure 4

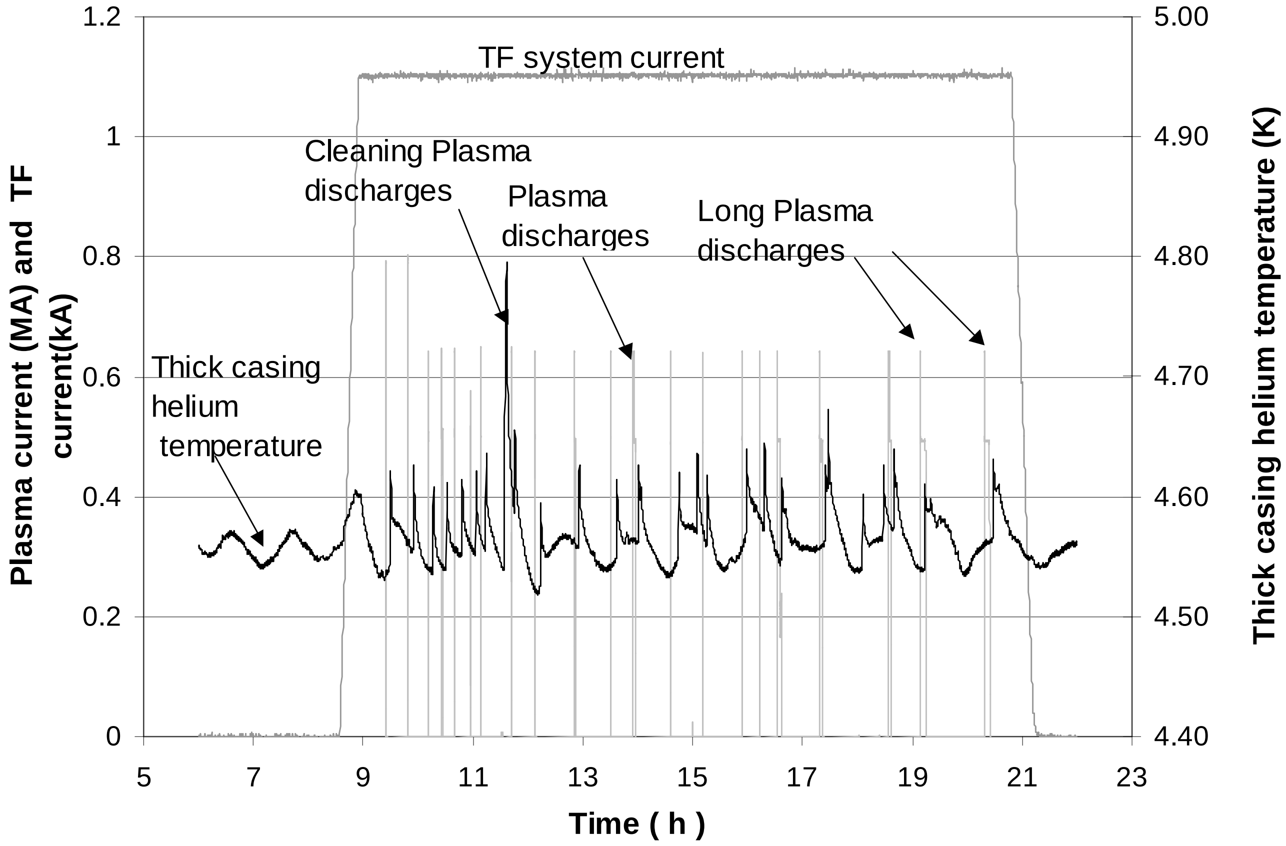


Figure 4: Thick casing helium temperature during one day of operation

J.L Duchateau Figure 5

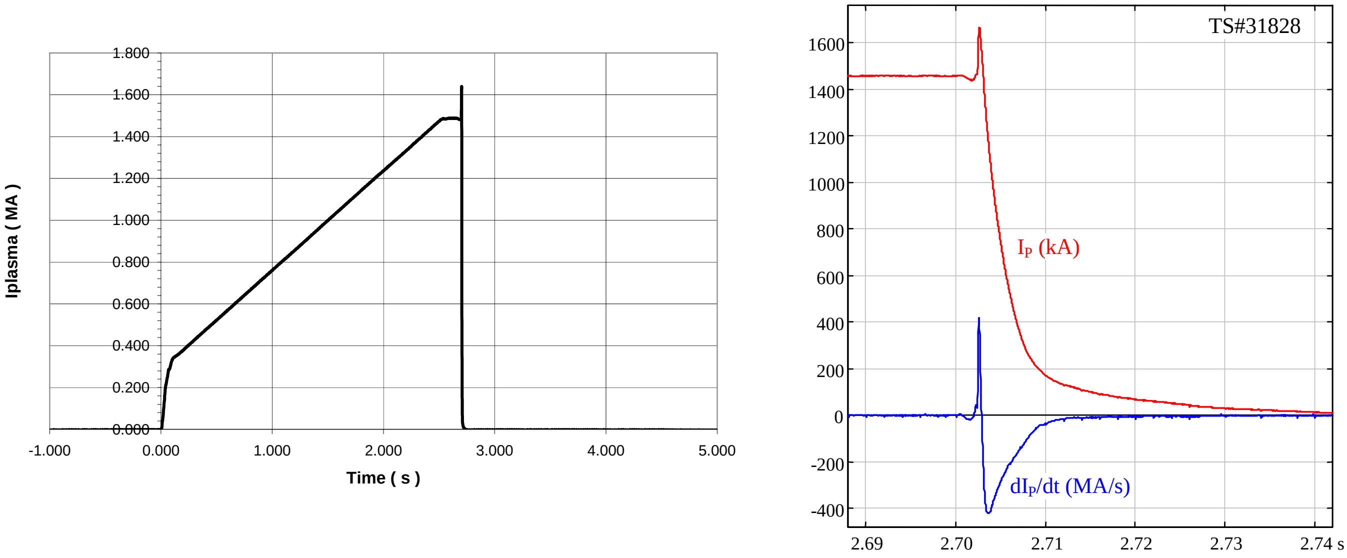


Figure 5 : Plasma current evolution (two times scales) during a disruption from 1.7 MA

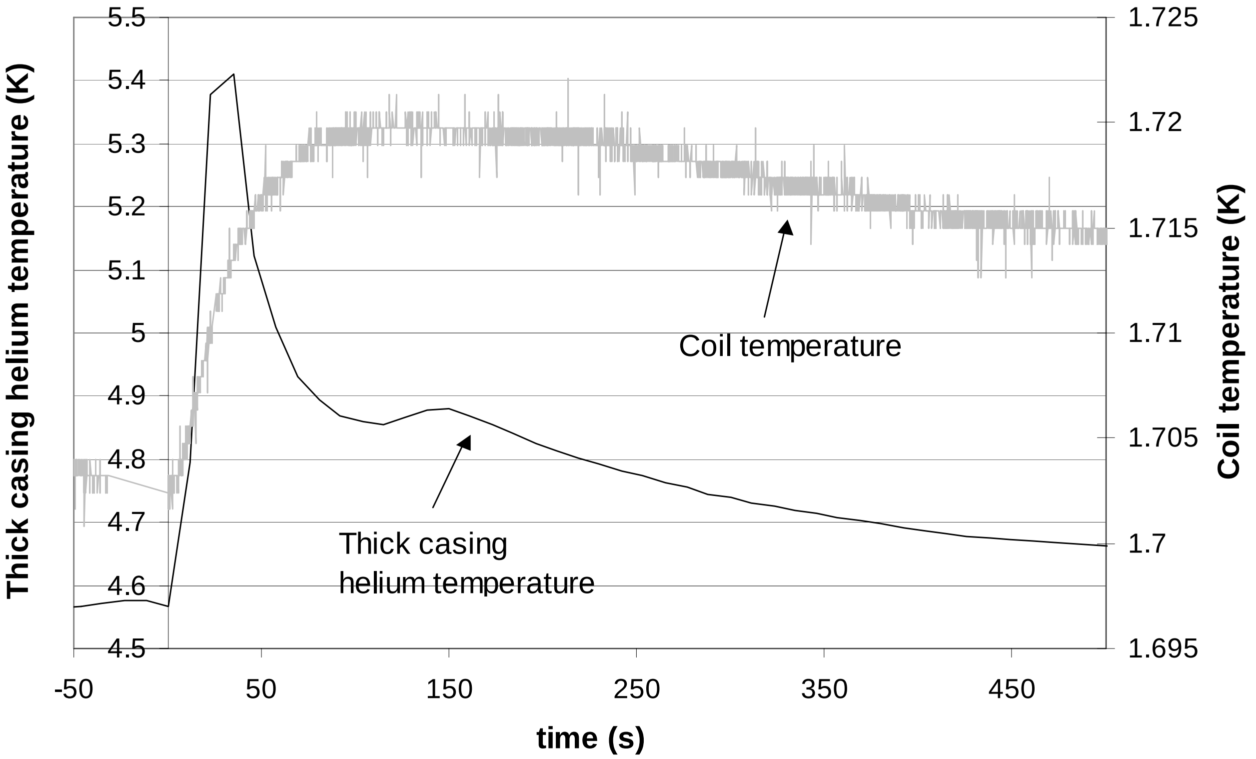


Figure 6 : Cryogenic impact due to a disruption from 1.7 MA

J.L Duchateau Figure 7

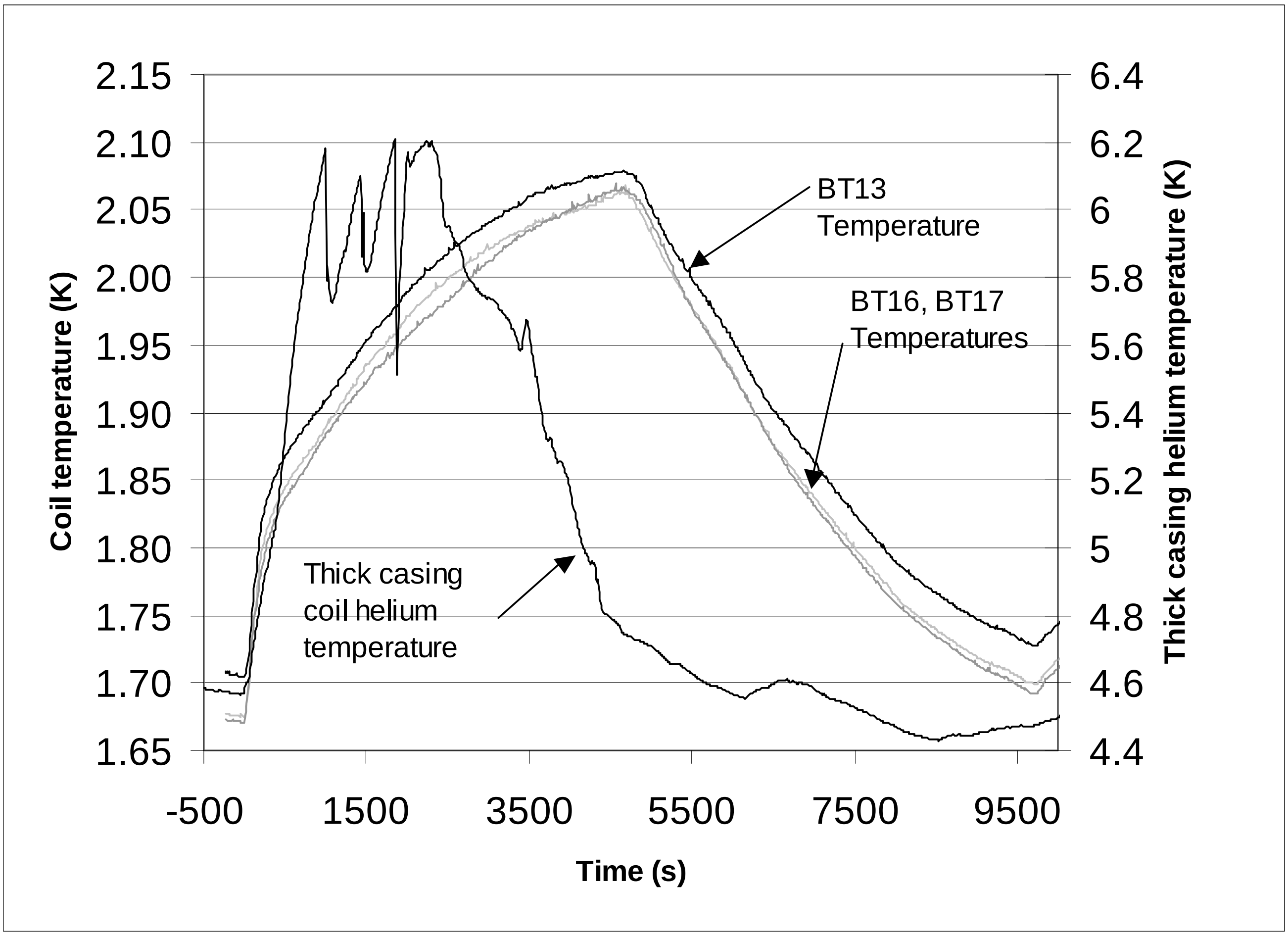
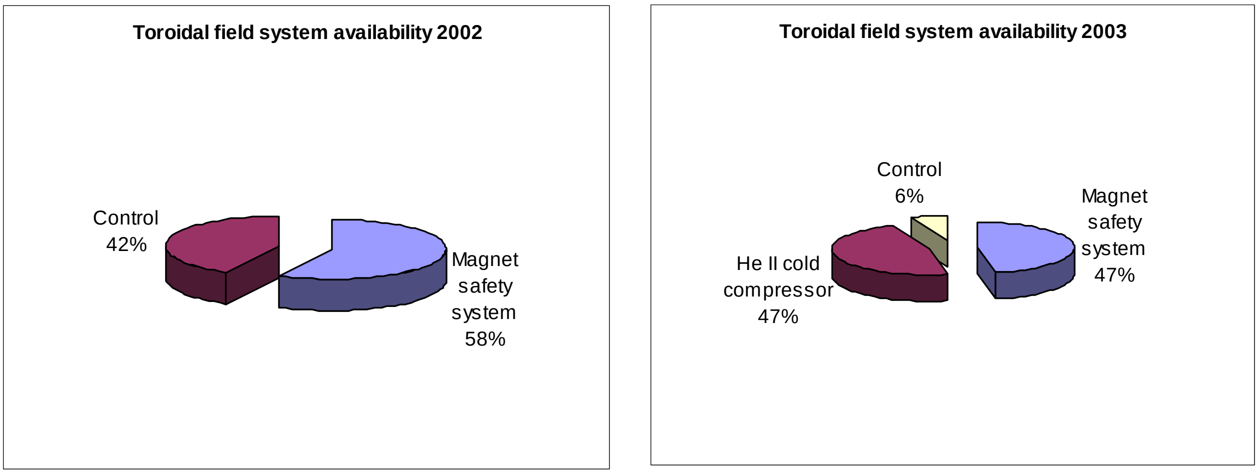


Figure 7 : Cryogenic impact of a fast discharge from a 1250 A TF current

J.L Duchateau Figure 8


Toroidal field system availability 2002

Toroidal field system availability 2003

Figure 8: Non availability distribution of TS magnet system in 2002 and 2003.

References

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