The superconducting TF magnetic system of Tore Supra

Jean-Luc DUCHATEAU (CEA Cadarache)

Association EURATOM-CEA, CEA/DSM/IRFM


50T-5T
ADC

1. Introduction
TORE SUPRA TF system contribution

The **revolution** of superfluid helium 1.8 K

TORE SUPRA

Introduction of a new type of refrigeration for sc on an industrial level
Thousands of litres in TS (1988)
Hundredths of thousands litres in LHC (2007) !

Cryoelectricity for magnet systems can be handled together with Plasma Physics in large fusion experiments

Introduction

GENERAL OBSERVATIONS

The toroidal field system of TORE SUPRA is one of the largest superconducting system in operation.

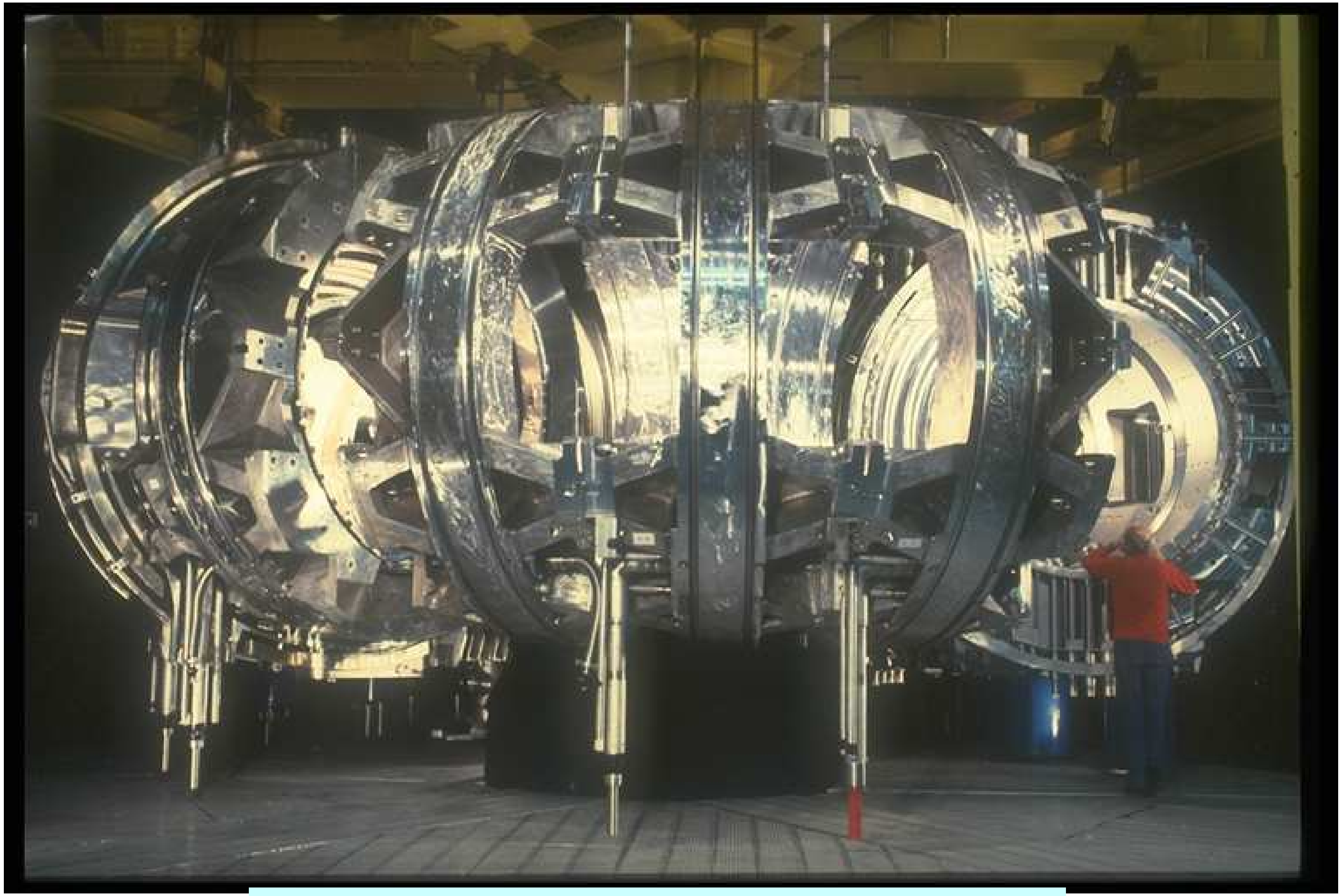
It is operated near its nominal characteristics since November 1989.

The system is operated daily, the field is increased typically in the morning (8 am), maintained during the whole day long and decreased in the evening around 8 pm.

Very good reliability and availability of the refrigerator including for the first time industrial quantities of superfluid helium thanks to the Claudet bath.

The non cycled operation of the magnet leads to a simplification in the preparation of the shot. Most of the conventional toroidal field systems of large tokamaks experience on the long run problems connected to the cycling and resulting mechanical fatigue.

Introduction



The Tore Supra TF magnet during assembly

Mains aspects of Tore Supra design

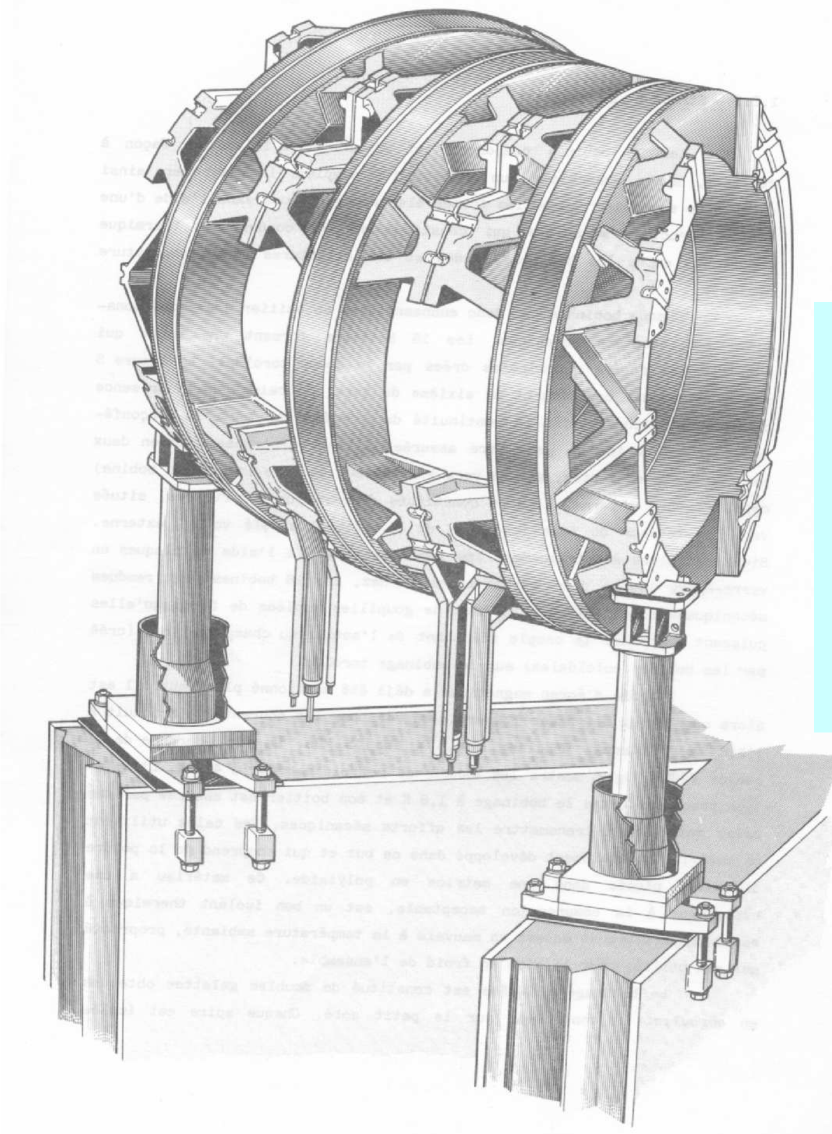


FIG. 5 - MODULE D'AIMANT TOROIDAL

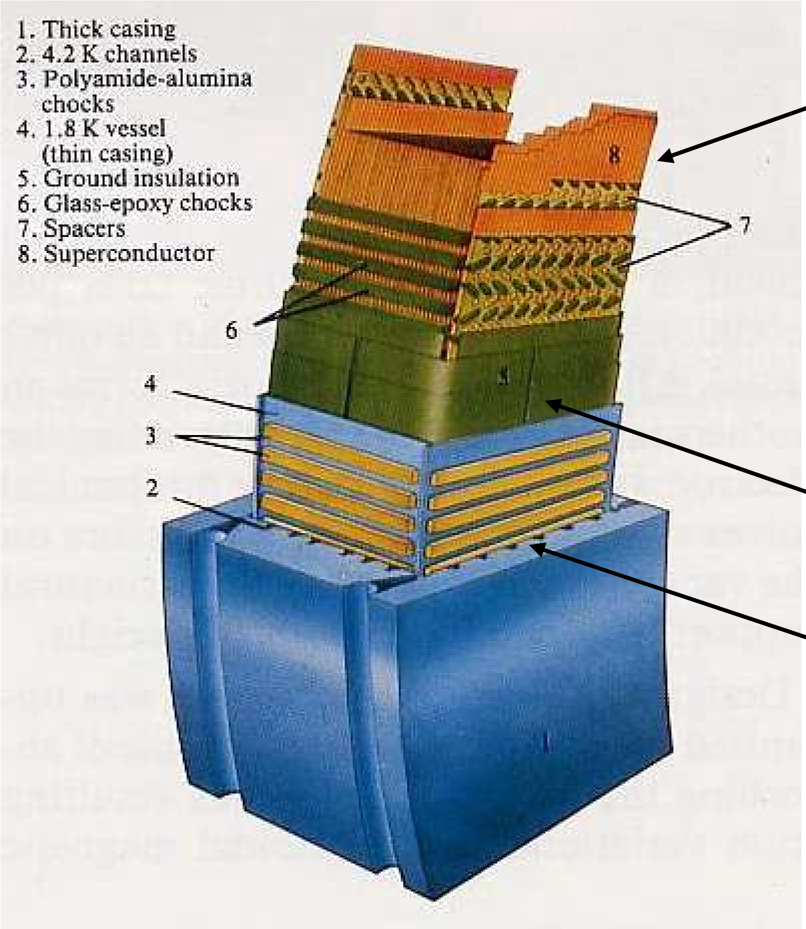
Figure shows one module representing 1/6 th of the magnet. It is made of two parts: the inner vault (or coil nose) is massive, the outer one (or coil ears) is made of a divided structure. The coils are electrically insulated from each other by glass epoxy plates while being mechanically locked by insulated shear keys.

A module of the Tore Supra TF system (1/sixth of the TF system)

Mains aspects of Tore Supra design

The machine is composed of identical modules representing 1/6 th of the full torus. The modules, assembled separately, contain the complete succession of torus: inner vessel, thermal shield, magnet system, outer thermal shield, and outer cryostat. After assembly, each torus behaves as a rigid torus, so that forces acting on it are self-restrained. The implication and the advantage is that only the weight has to be supported by components at a different temperature.

Mains aspects of Tore Supra design



Tore Supra TF coil structure

bare conductors in superfluid helium !

Superfluid helium (1.8 K) in thin casing

Supercritical helium (4.5 K) in thick casing channels

Mains aspects of Tore Supra design

At the bath temperature (1.8 K), at 1400 A and 9 T the conductor satisfies stability requirements of two kinds:

- In case of a plasma current disruption, the conductor is subject to field variations in the range of 0.6 T with an associated time constant due to the steel casings of about 10-20 ms. The conductor must not reach at any point a temperature greater than the current sharing temperature.

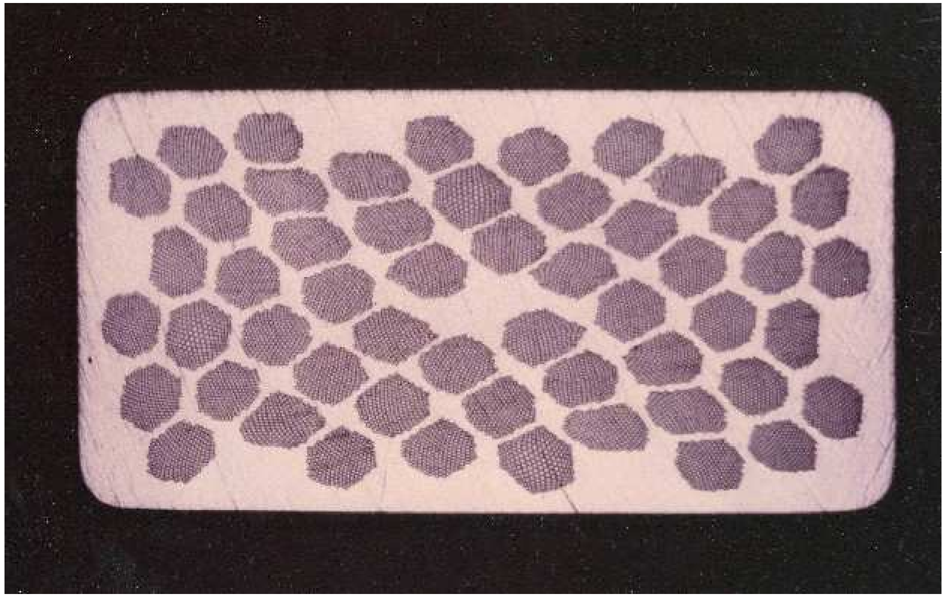
- In case of a sudden temperature increase caused by accidental perturbation the conductor temperature can increase above the critical temperature and recover after having reached the following typical values: 30 K for a localized perturbation under one spacer, and 15 K if a whole pancake is affected.

Mains aspects of Tore Supra design

As a consequence, in the TF coils, the operating point was chosen such as to absorb perturbations and plasma current disruptions. On the load line the critical current is reached at 4.2 K, for the nominal TS values (1400 A and 9 T). Local losses in the conductor in operation and in particular during disruption ($\Delta B = 0.5$ T within 10 to 20 ms) must remain sufficiently small to be absorbed by the very large enthalpy of superfluid helium between 1.8 K and 2.16 K (T_λ): 3 10^5 J/m^3 .

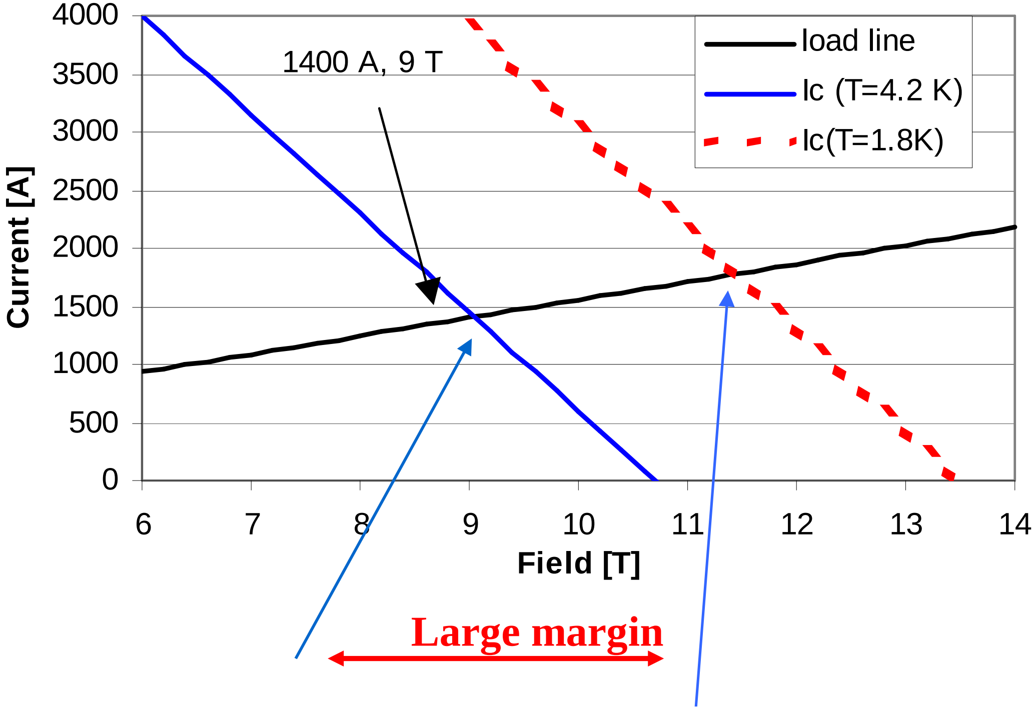
Not all the conductor lengths are in direct contact with superfluid helium. Thermal temperature gradients arise during heat extraction in the non-wetted parts of the conductor. The current sharing temperature of the project has been adjusted to take into account with a margin the highest temperature during the process of heat extraction. This temperature has been estimated around 3.4 K, which means that the margin compared to the current sharing temperature of 4.2 K is **0.8 K**.

Mains aspects of Tore Supra design



Tore Supra TF system conductor (2.8 x 5.6 mm^2)

Mains aspects of Tore Supra design



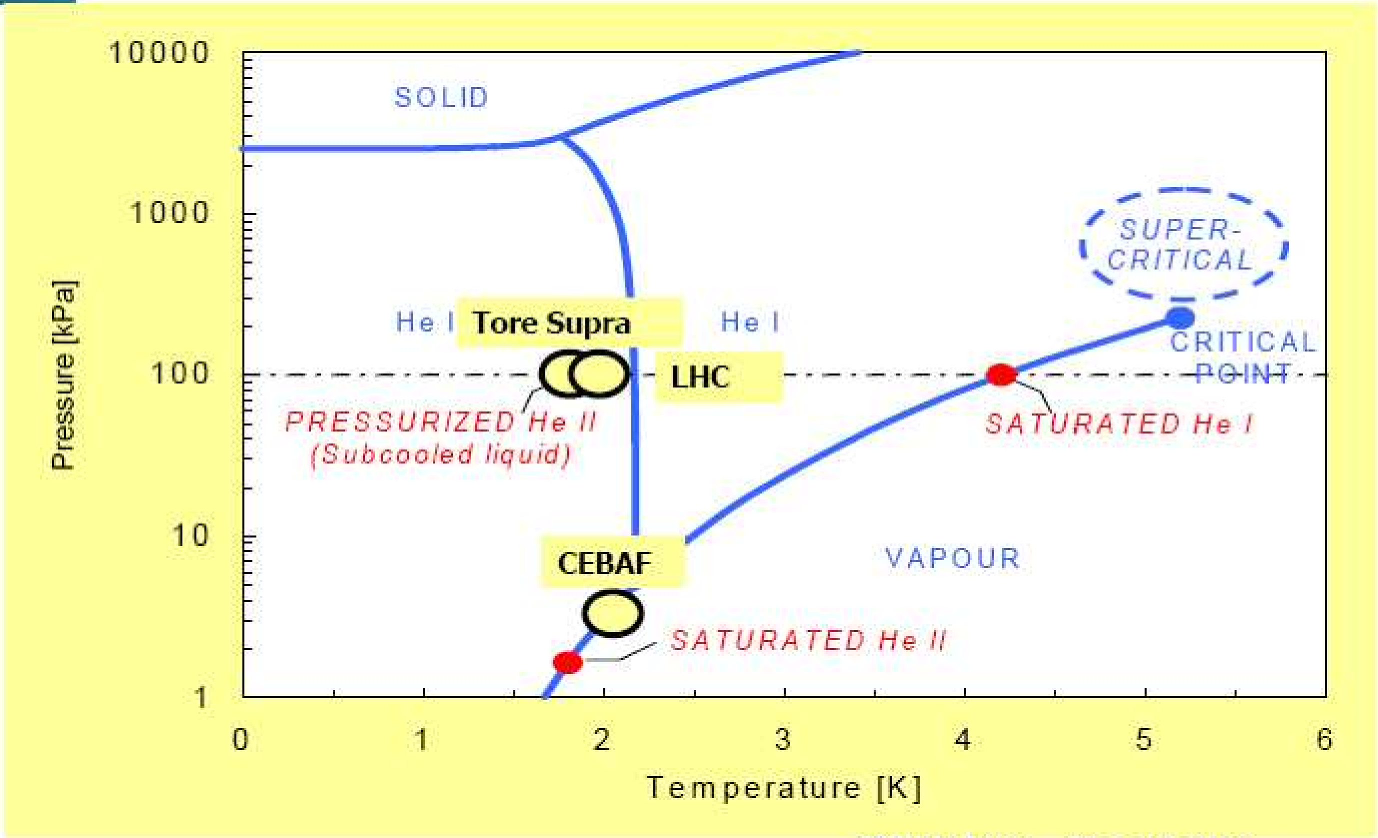
Large margin

Operation point

Critical point

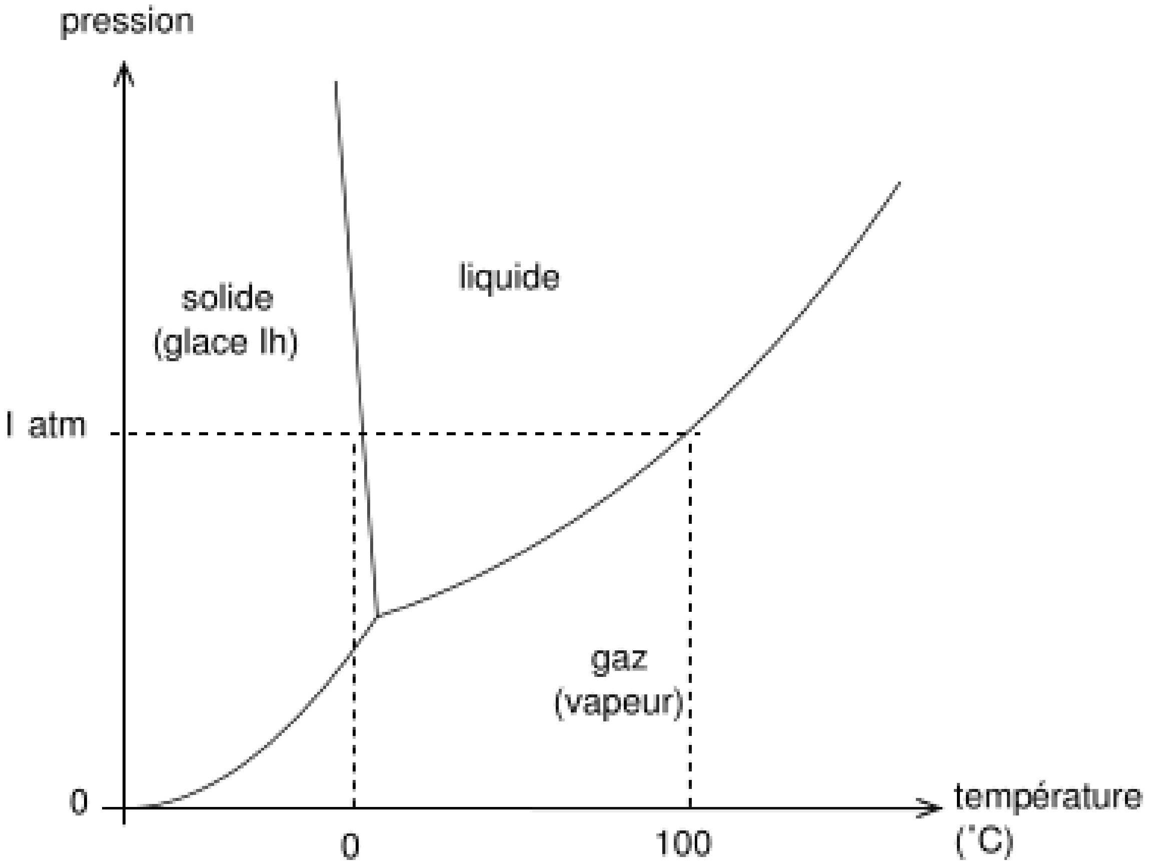
2.4 K Temperature margin on the TF system of TS on all the coils except BT19

Cooling with superfluid helium



Cf P. Lebrun - Presentation - Wednesday 9.50 am

Phase diagram of water
(To be compared with helium)



Acceptance tests
Before assembly at CEA Saclay

The acceptance tests of the coils before assembly were performed at CEA Saclay. Three objectives have been assigned to these experiments:

Test of the prototype coil which was specially equipped with small heaters to induce a quench, and voltage taps to study the propagation of the normal zone.

Test of the 18 coils of the torus

Test of the equipment used for cooling and the electrical systems as pumps, superfluid heat exchangers, safety valves, leads and electrotechnical equipments.

Acceptance tests
Test of the prototype coil at CEA Saclay

- Observation on strain gages during cooling down
- Increase of current up to nominal current (1400 A)
- Fast discharge with a time constant of 14 s (1750 V)
- Initiation of a quench by a resistive heater and observation of the quench characteristics (main result: quench propagation within 3 s)

Main problems

- burning of a switch (wrong time control in the electronic system
- damage to the current breaker due to stray magnetic field
- transition because of operation at very low pressure (saturation pressure) (failure of cold valve opening during cooling down)

Acceptance tests
Tests of the series coils at CEA Saclay

tests before energizing

- 8 kV dc to the ground for one minute at room temperature
- 4 kV to the ground in superfluid helium with current leads connected
- tightness tests of the thin casing after cooling down

tests in current

- first check tests at 120 A
- 1400 A (5.4 T) with no training in all coils (9 T in TORE SUPRA)
- 1750 V across the coil during FSD (half nominal voltage)

Acceptance tests
Tests of the whole system at CEA Cadarache

- insulation tests
- tightness tests (thin casing),
- tests at 120 A,
- operation at reduced current 600 A associated with first campaign of TORE SUPRA.

→ **short circuit on BT17**

Replacement of BT17 by prototype coil transformed in spare coil

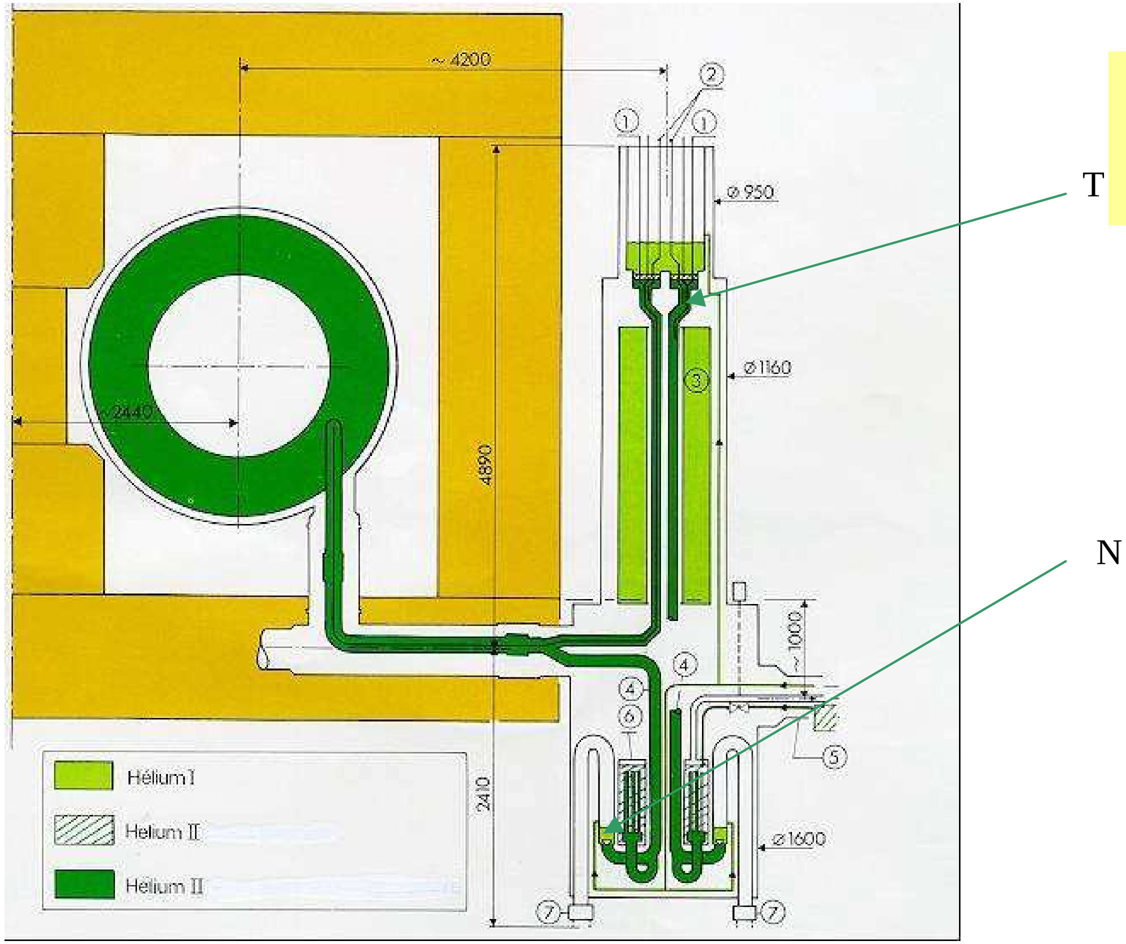
- change of safety system principle
- update of quench detection system and of system monitoring
- acceptance tests by step (120 A, 600 A, 800 A, 1000 A, 1250 A, 1450 A) FSD at each step
- observation of abnormal behaviour on BT13 with eventually quench during 1450 A FSD.

Insulation tests after each (warm up – cooling down cycle) of the system : test to the ground of each coil, capacitor discharge on each coil with comparison with previous results, strain measurements (gauges on thick casings) on current cycle.

Protection in case of a quench
The detectors

	V **Voltage** (V)	P **Cold pressure** (Pa)	N **Cold Liquid** **In cold valve region** (K)	T **Temperature near** **Current lead cryostat** (K)	I **Ground current** (A)
Thereshold level	<2.	$<2.\ 10^5$	>1.95	<2.05	50.
Time delay (s)	1.	0.5	2	2.	0.5

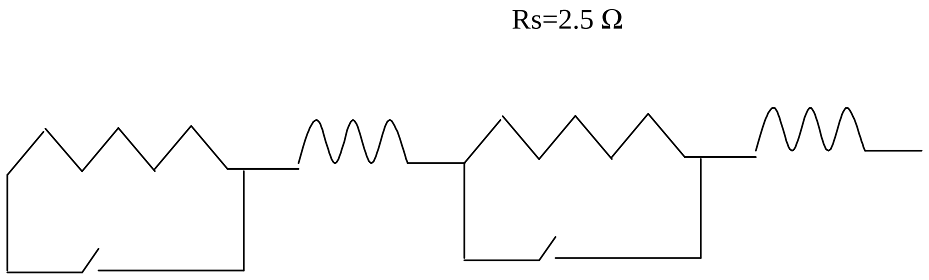
Protection



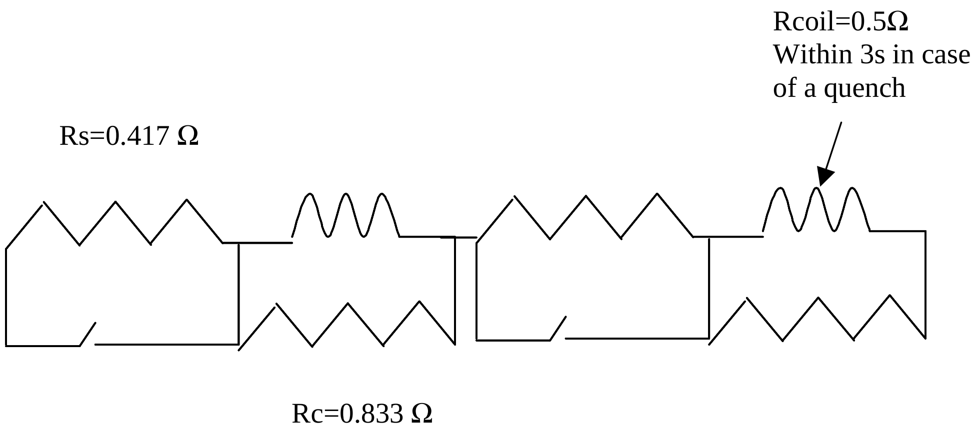
Location of the two temperature detections

Protection

Evolution of the discharge circuit after damage of coil BT17 (two cells)



Original protection design



New protection design

Protection

Tore Supra TF system FSD resistor

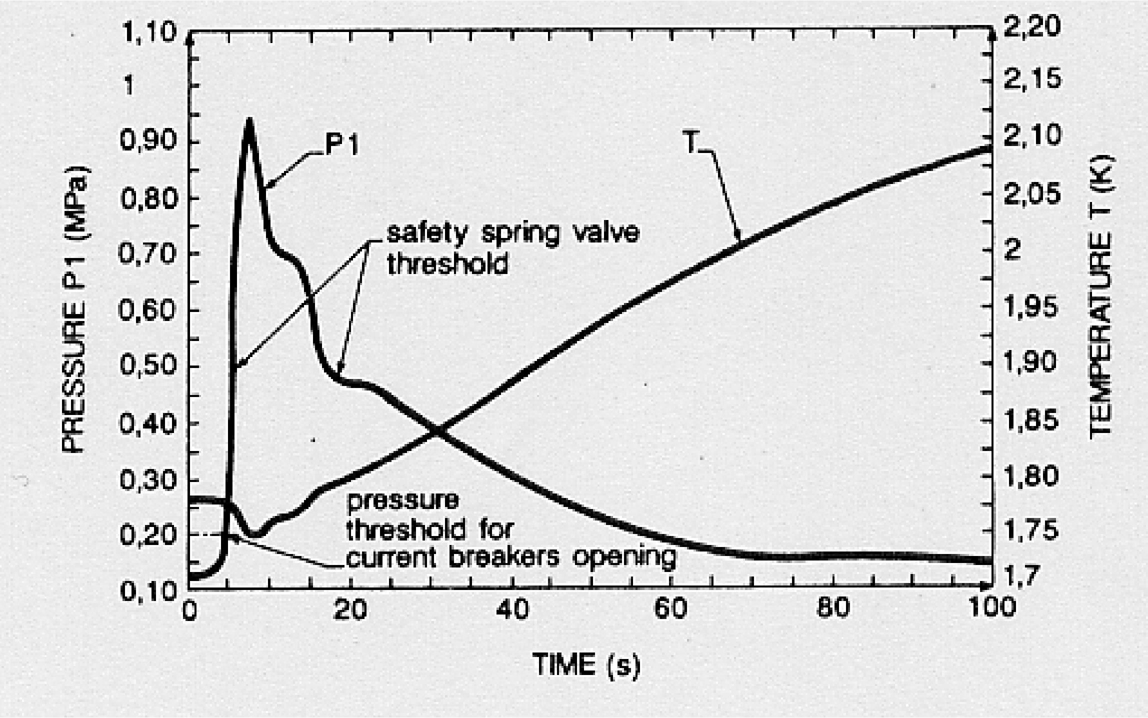
Protection

The rearrangement of the discharge circuit from a series circuit to a series/parallel circuit has allowed **to decrease the voltage across the coil by a factor of ten**.

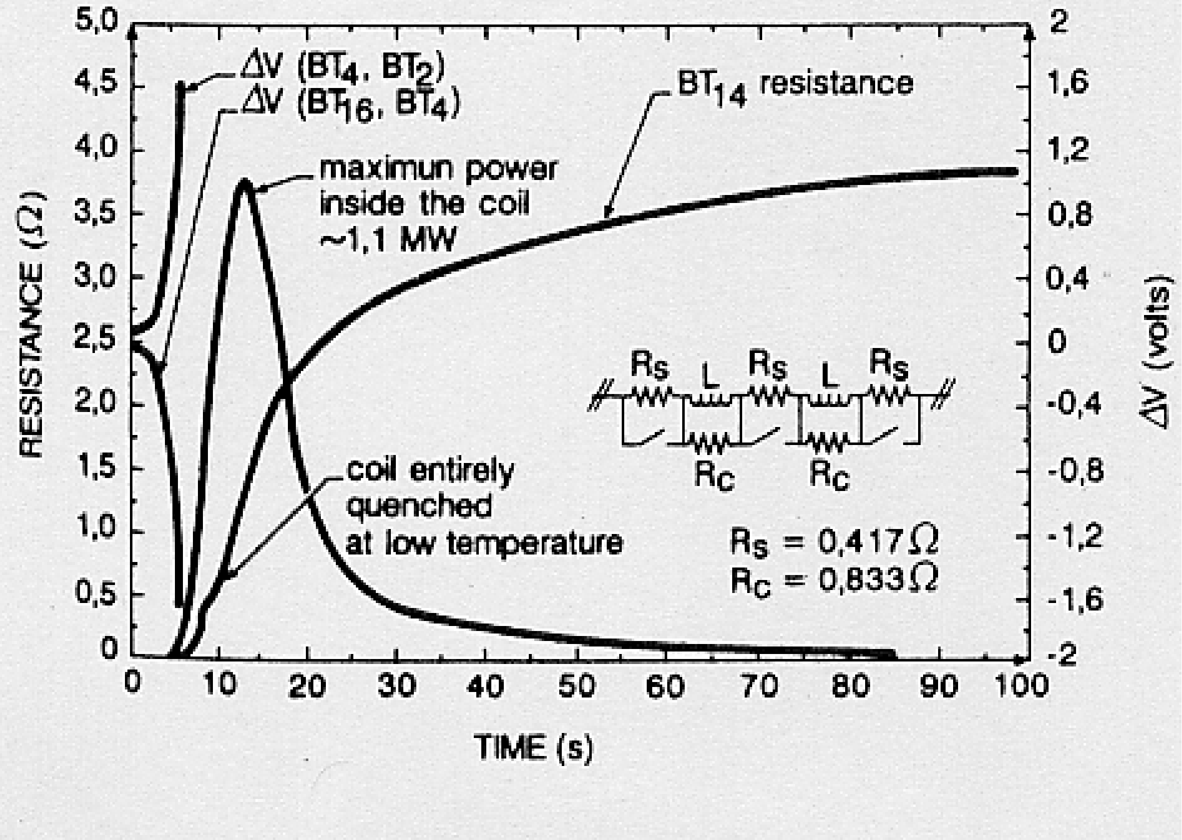
- in case of a FSD without a quench the voltage across the coils is low (390 V instead of 3500 V) and the time constant of the discharge is long 122 s.

- in case of a real quench, the electrical circuit is affected by the resistance of the quench coil which is rapidly (3s) at a value around 0.5 Ω decreasing **automatically** the time constant discharge of the quenched coils around 14s, which is adequate to protect it.
Unbalance of current between coils and associated shear forces have been studied and accepted.

Unique quench in TORE SUPRA Coil BT04



Unique quench in TORE SUPRA Coil BT04



Protection

Check of the quench detection system

This check is performed daily and automatically on the three main quench detections (T,P,V).
As concerns the temperature detection the alarm must be triggered on every coil during the night warming up. This transition is automatically checked afterwards every day, attesting the good behaviour of the whole detection system.

For the pressure and the voltage detections the test is made by simulating a quench signal and checking that it is well detected. An additional test is made on the voltage detection to ensure that the time delay is well respected and that the detection cannot be triggered by a simple electrical noise.

Status of the Tore Supra TF system

1982-1988 **coil manufacture and magnet assembly**

→ **all coils** tested up to **nominal current** (1400 A) at Saclay

1988 **start of operation**

→ **short circuit** in BT17 during a fast safety discharge

1989 **replacement of BT17 by spare coil BT19**

acceptance tests of TF coils up to 1450 A (9.3 T)

→ **quench** of BT13 during fast safety discharge (FSD)

→ limitation of operating current to **1250 A**

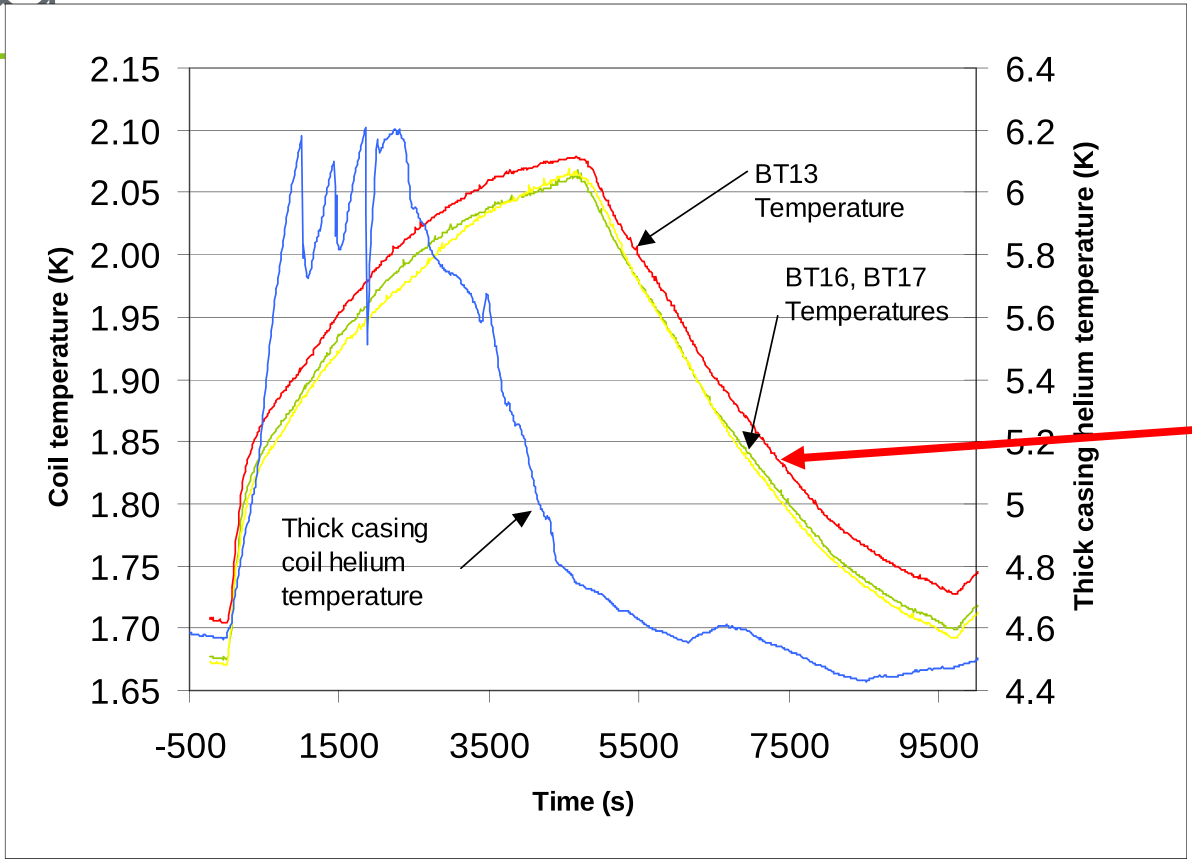
→ temperature increase observed in BT13 during FSD

1995 **disappearance of defect on BT13**

→ no more temperature increase in BT13 during FSD

2002 **continuous data acquisition system**

Status of the TORE SUPRA TF system
No more apparent problem on BT13



Temperature increase in coils during FSD (2003)

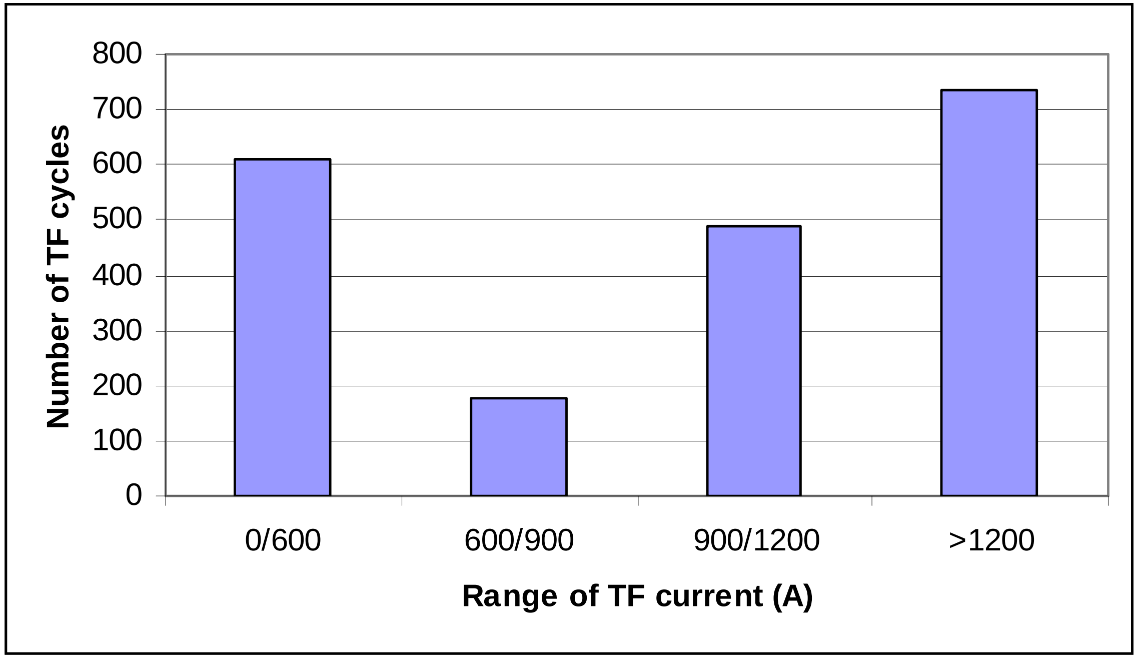
No special cryogenic impact of FSD in BT13 in comparison with the other coils

Green light for TF operation 1.8 K

Normal operation in TORE SUPRA

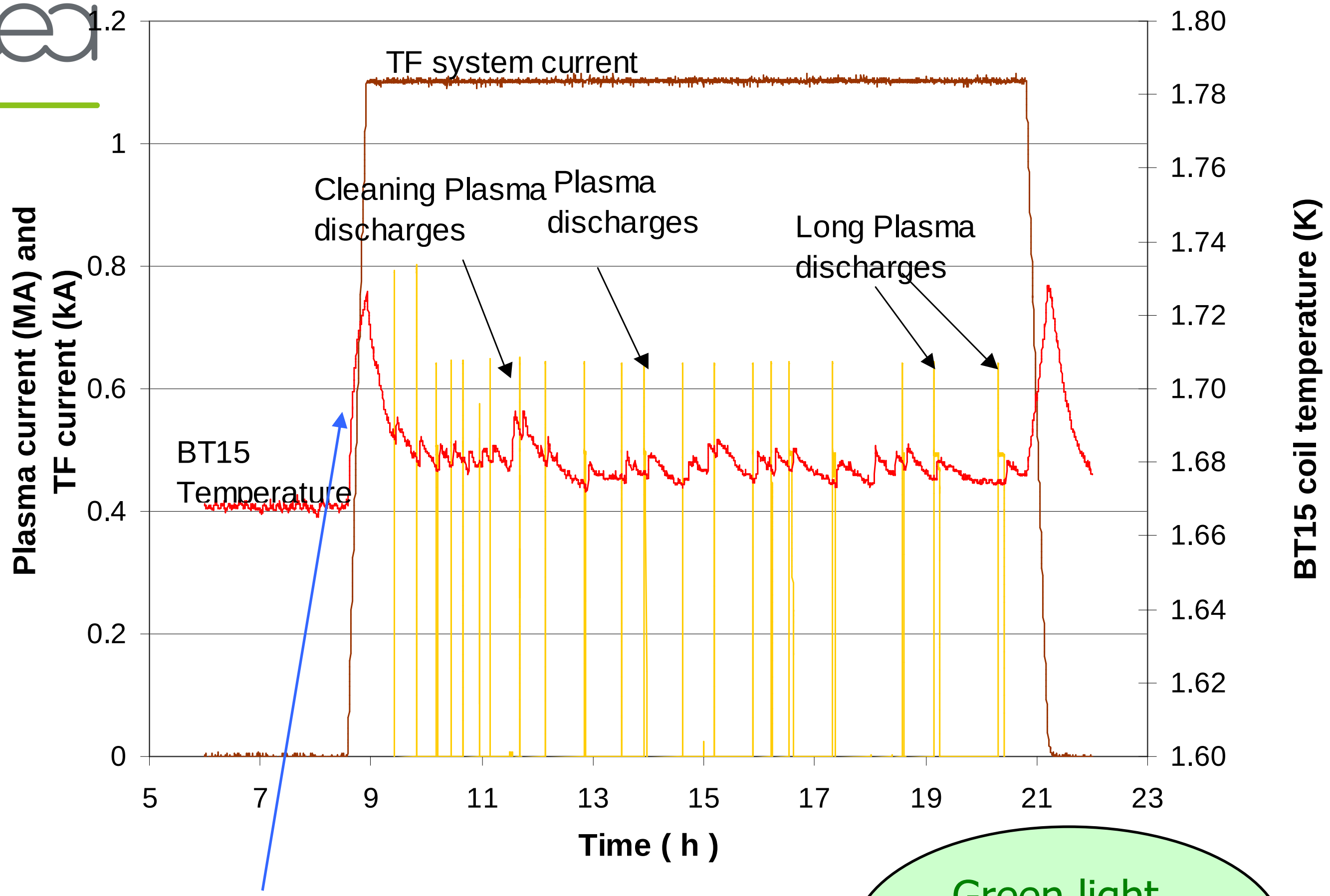
Thermal cycling: 16 thermal cycling were performed since 1988 for the TF system (300 K→ 1.8 K→300 K)

Plasma discharges: 25500 plasma discharges have been performed.



TORE SUPRA
TF activity
Since 1988
11000 hours of
operation

Normal operation in TORE SUPRA



Since 2003 continuous data acquisition and record on TF sensors available

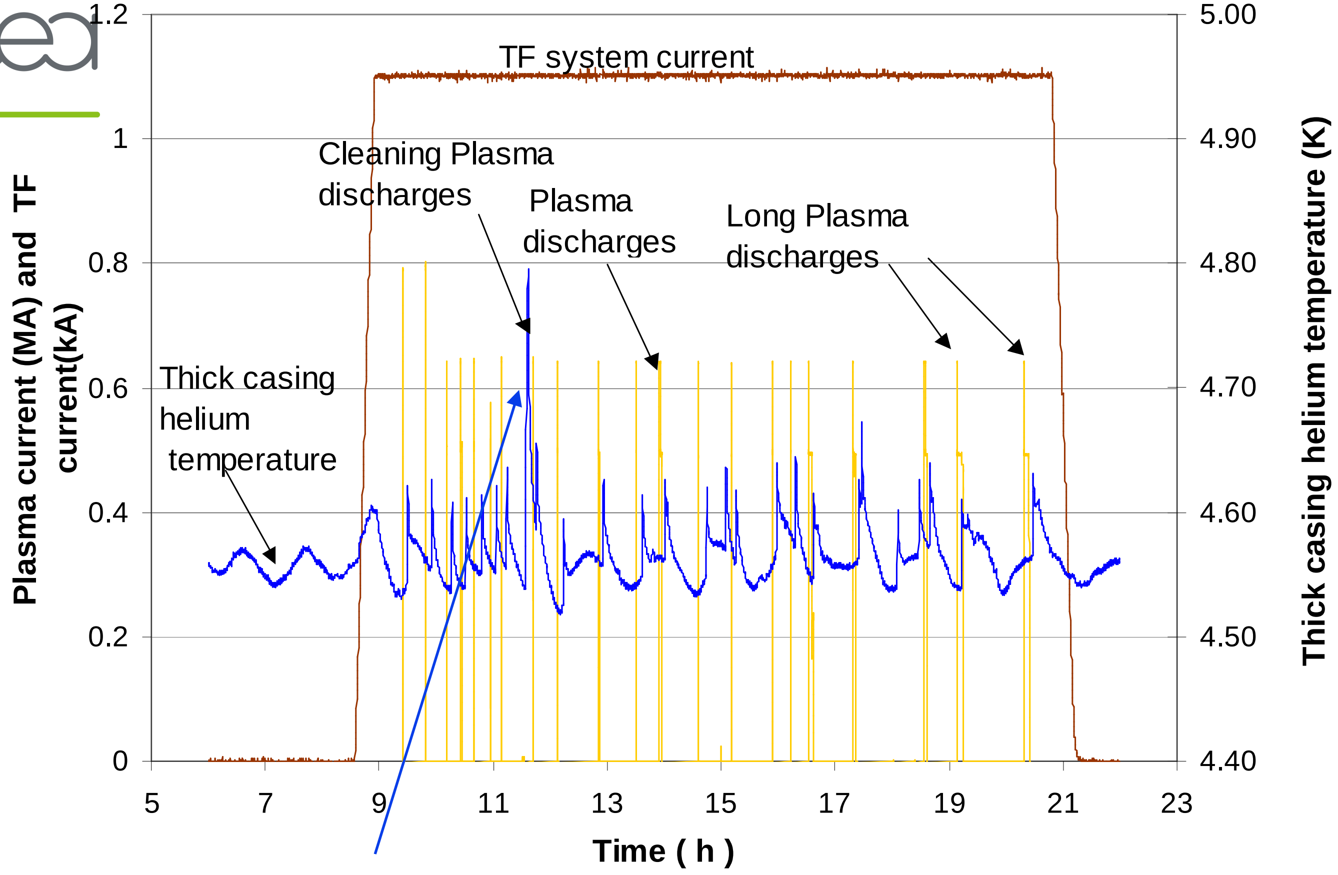
Better system monitoring is possible

Temperature increase linked to TF current increase (0.06 K)

Green light for TF operation 1.8 K

BT 15 temperature during one day of operation

Normal operation in TORE SUPRA



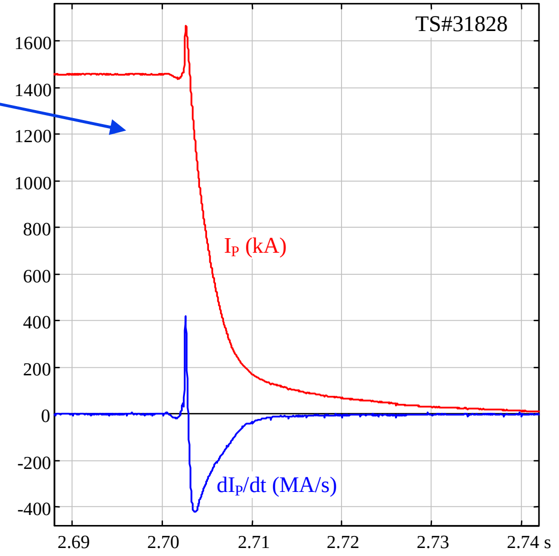
Thick casing helium temperature during one day of operation

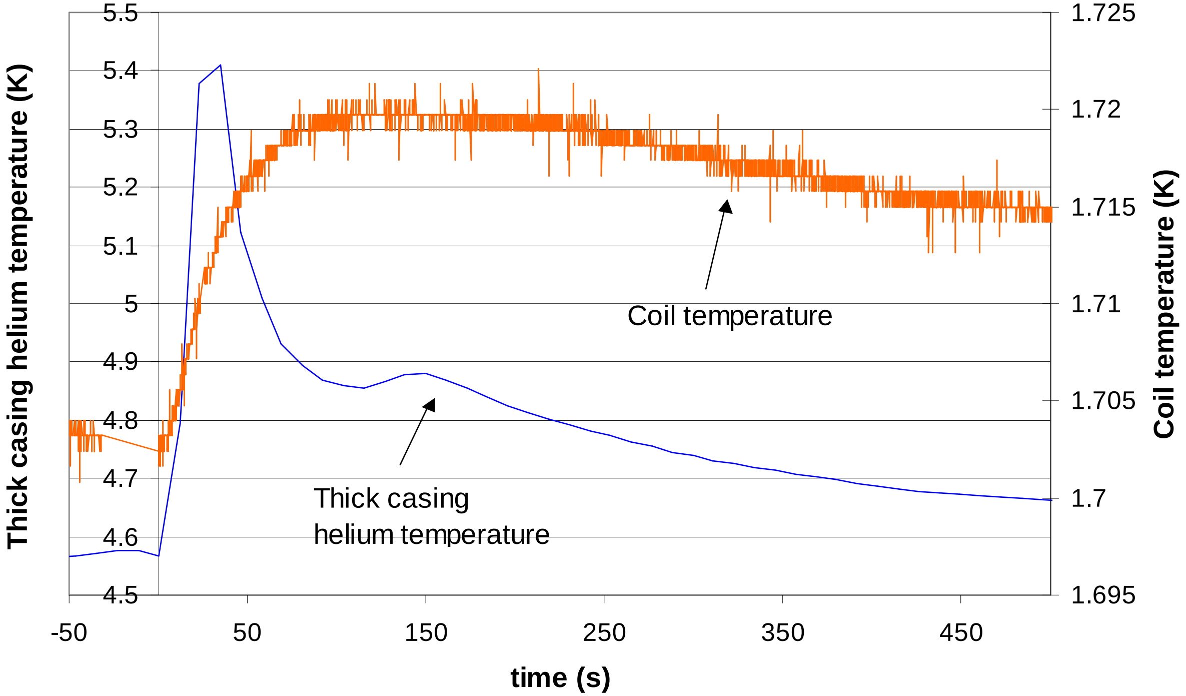
Temperature increase linked to cleaning plasma discharges

Normal operation in TORE SUPRA

Green light
for TF operation
1.8 K

Plasma disruption





Cryogenic
impact due to a
disruption
from 1.7 MA
0.02 K for coil
0.83 K for thick casing

Main problems in operation: FAST SAFETY DISCHARGES

Every year several FSD in the TF system. They 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.

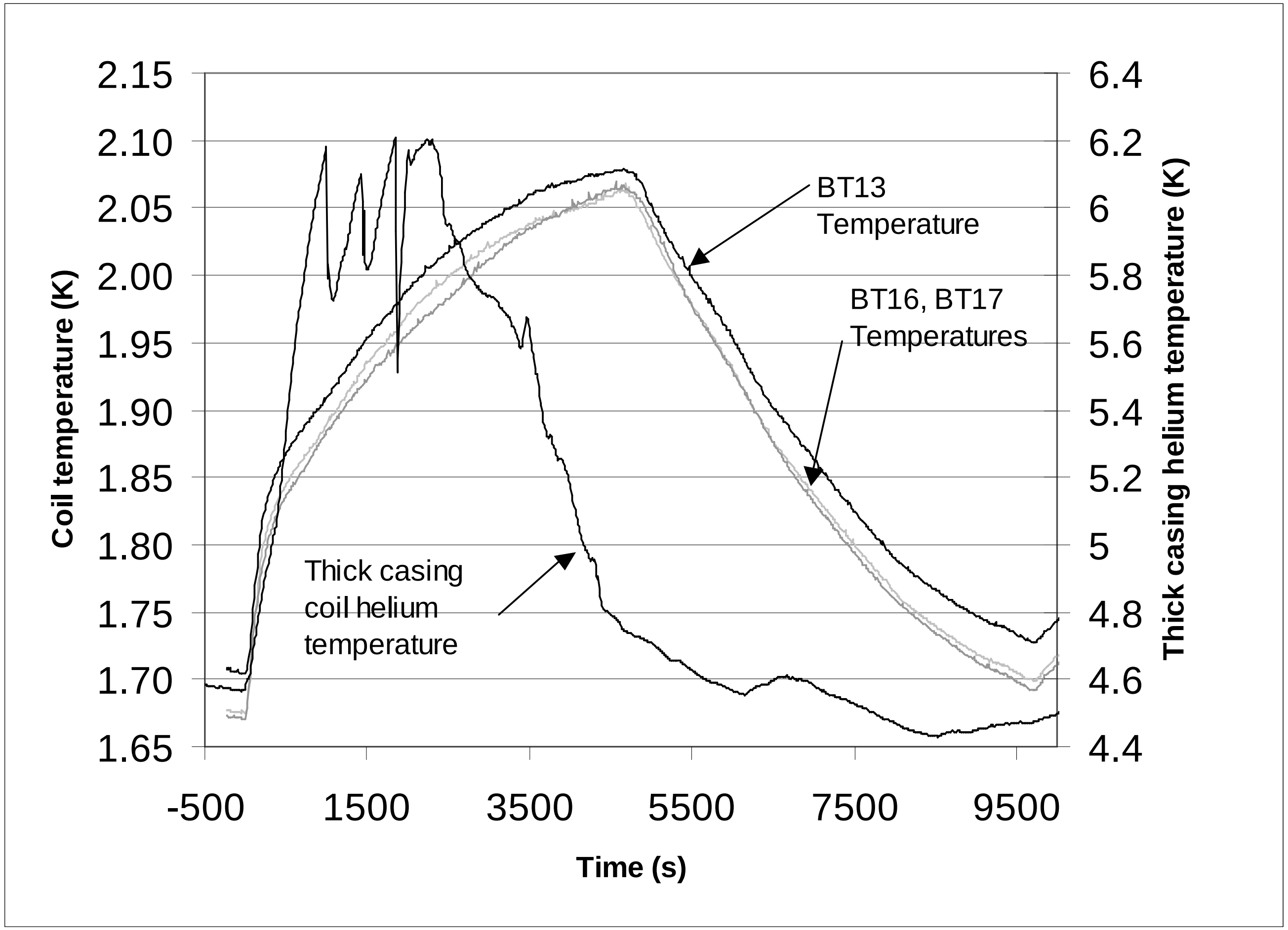
During FSD the coils experience the largest voltage in operation (320 V corresponding to 1400 A). The weak point of the system is the presence of bare conductors and the associated possibility of short circuits → FSD have to be avoided

FSD induces a thermal load on the system which need on average 2h30 to recover and the operation is correspondingly interrupted. Part of the FSD are associated to electrical perturbations during plasma heating.

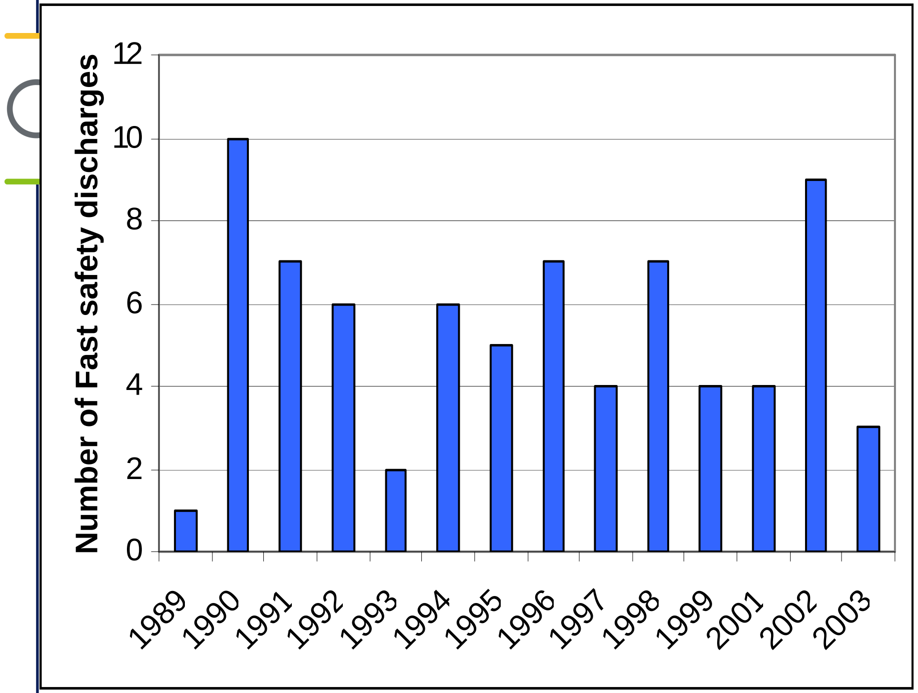
↓

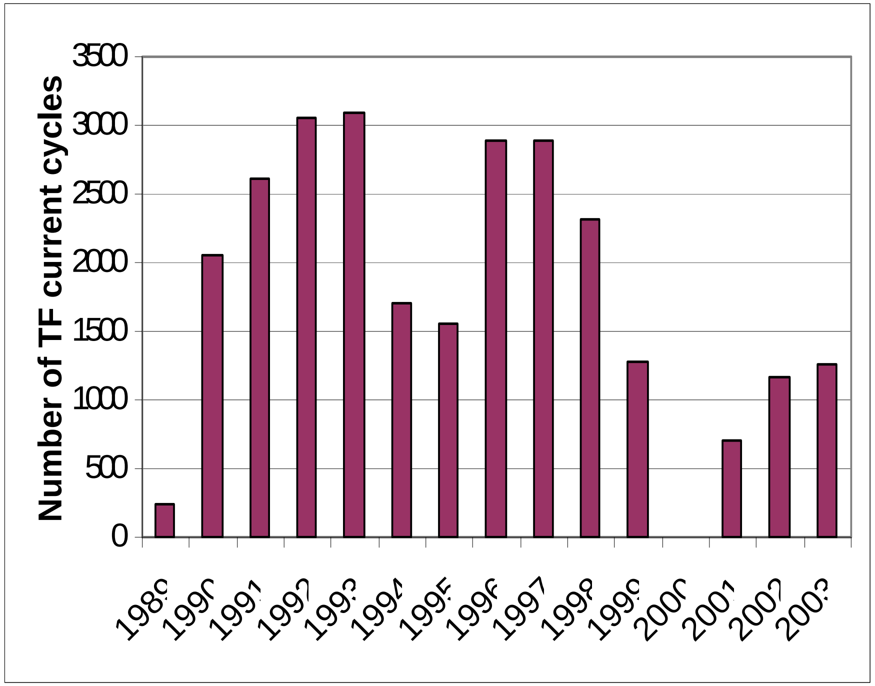
To mitigate the perturbation on the Tokamak operation an important effort was devoted to make the protection system of TS magnets more insensitive to electrical perturbations.

FAST SAFETY DISCHARGES



Main problems in operation: FAST SAFETY DISCHARGES



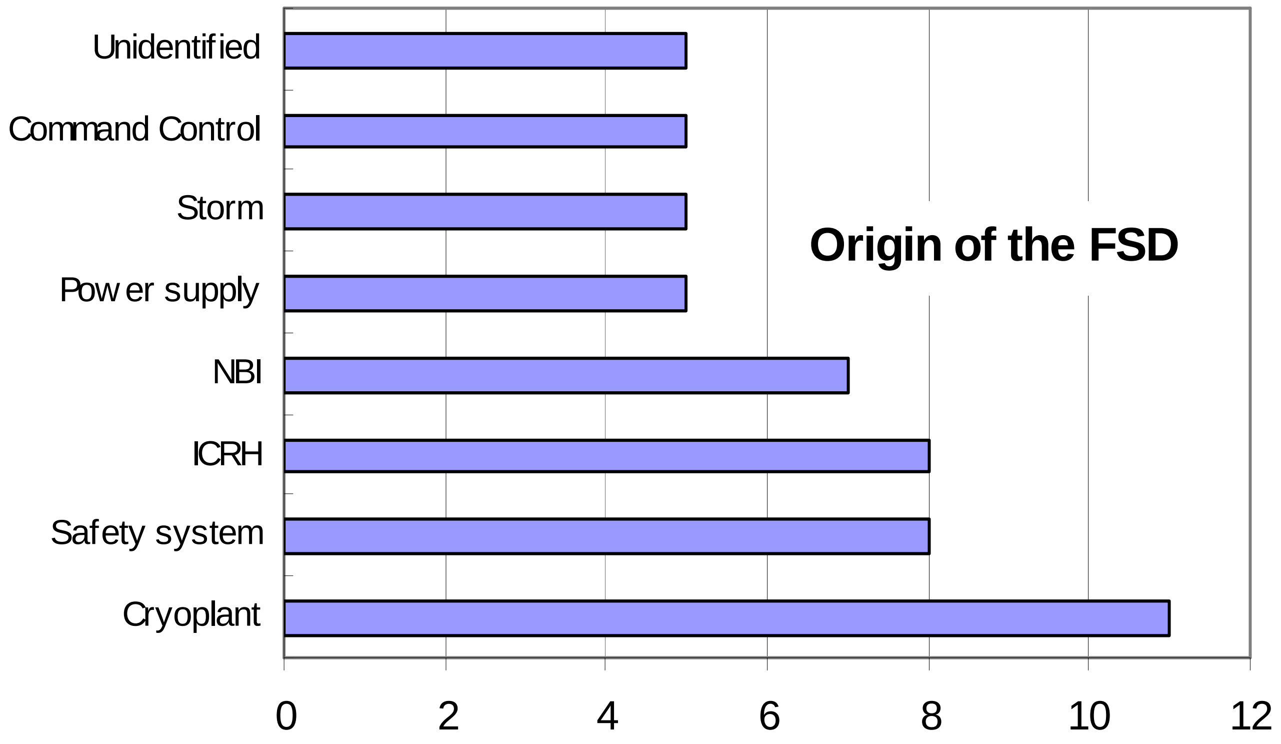


Mitigation of perturbation

Using time delays on alarms as long as possible without affecting the protection of the coils in case of a real quench.

Important effort in sensors conditioning→ general protection optimisation

FAST SAFETY DISCHARGES



Temperature increase linked to cleaning plasma discharges

The cryogenic system of TORE SUPRA
Power associated to operation modes

	77 K Power 6000 l of N_2 Per 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
Week ends	10 kW	700 W	0	900 kW
One week shut down	10 kW	0	0	300 kW

Cryoplant fully automatic operated by a team of 12 people

0.5 Meuros/year Excluding staff and energy

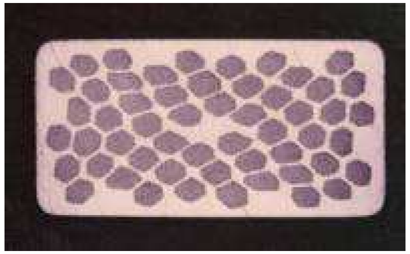
The cryogenic system of TORE SUPRA
The major tendency of the cryoplant ageing

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.**

Can the TF magnet experience of TS be useful for ITER ? How far are TORE SUPRA and ITER TF systems comparable ?

TORE SUPRA TF system	ITER TF system
600 MJ 1400 A 500 V Superfluid bath No radial plates	40 GJ 68 kA 10 kV Forced flow cooling Conductors in radial plates



TORE SUPRA conductor
2.8 x 5.6 mm
NbTi

ITER model coils conductors
51 x 51 mm
¢=40.7 mm
Nb3Sn

How far are TORE SUPRA and ITER TF systems comparable ?

TORE SUPRA operation cannot be simply extrapolated to ITER

Forced flow cooling introduces a completely new type of refrigeration
This is linked to very high voltage monitoring

Forced flow cooling induces a different kind of protection strategy

Radial plates solution impose a more difficult operation mode with cold eddy current. FSD contrary to the situation in TS induces a quench

Specific solutions have to be developed for ITER

How TORE SUPRA experience on TF system is useful for ITER magnet system ?

Practical demonstration during this 16 years that Plasma Physics is possible with superconducting magnets. **ITER decision could probably not be possible without this experience**

This experience has been transferred during ITER R&D programs for ITER conductor design and coils design by CEA magnet team.

Still to be done
Experience in TS can help

- Design of simple and robust protection and monitoring system specificities such as plates and related impact on cryogenics during FSD
- Double contradictory objective

→ **Avoid quench system (40 GJ) (only one quench since 1988 in TS !)**
→ **Minimize number and effect of FSD because of plates**

- Detailed magnet operation concept,
- Refrigeration dimensioning as a function operation specifications

Conclusion

The TORE SUPRA Tokamak is 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 which can have an impact on ageing of insulation.

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.