Forschungszentrum Karlsruhe
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FZKA 6614

ITER Toroidal Field Model Coil (TFMC) Test and Analysis Summary Report (Testing Handbook)
Chapter 3
TOSKA FACILITY

Compiled by:
A. Ulbricht
with contributions from:
M. S. Darweschsad, S. Fink, G. Friesinger, R. Heller, W. Herz, A. Kienzler, A. Lingor, V. Marchese, I. Meyer, G. Nöther, G. Schleinkofer, M. Süßer, F. Wüchner, G. Zahn
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ITER TFMC Test and Analysis Group

European Home Team

Forschungszentrum Karlsruhe GmbH, Karlsruhe

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Preface

The report contains the work of the Testing and Analysis Group of the European Home Team within the international ITER collaboration for testing the ITER TF model coil. The work was elaborated in meetings taking place at CEA Cadarache and Forschungszentrum Karlsruhe over about 5 years. The report consists of 5 chapters. Each chapter is printed as separate booklet.

J. L. Duchateau (Deputy Test Group Leader)
A. Ulbricht (Test Group Leader)

ITER Toroidalfeld-Modellspule
Zusammenfassender Bericht zum Test und zu den Berechnungen
(Handbuch zum Test) Kapitel 3 TOSKA-Anlage

Zusammenfassung

Im Rahmen eines Vertrages zwischen dem ITER (International Thermonuclear Experimental Reactor) Direktor und dem europäischen Home Team Direktor wurde die Erweiterung der TOSKA Testeinrichtung des Forschungszentrums Karlsruhe als Testbett für die ITER Toroidalfeld Modellspule (TFMC), eines der 7 großen Forschungs- und Entwicklungsprojekte der ITER EDA (Engineering Design Activity), beschlossen. Der Bericht beschreibt die Arbeiten und Entwicklungen, die gemeinsam mit der Industrie durchgeführt wurden, um die vorhandenen Anlagenkomponenten zu erweitern und durch neue Komponenten zu ergänzen. In diesem Rahmen erhielt die TOSKA-Anlage eine neue 2 kW Kälteanlage einschließlich der kalten Zuleitungen für die Heliumkryostate der TOSKA-Anlage. Die Meß- und Regeltechnik einschließlich der Datenerfassung wurde entsprechend dem Stand der Technik erneuert. Zwei vorhandene Netzgeräte (30 kA, 50 kA) sind durch Parallelschaltung über ein Al-Stromschienensystem als Stromquelle für 80 kA ertüchtigt worden und wurden durch einen Entladekreis für 80 kA ergänzt. Für den Test der TFMC im Hintergrundfeld der EURATOM LCT-Spule wurde ein neues 20 kA Netzgerät in Verbindung mit der vorhandenen 20 kA Schaltanlage in Betrieb genommen. Zwei forciert gekühlte Stromzuführungen für 80 kA für die TFMC wurden entwickelt. Die Gesamthubkapazität für Lasten in der TOSKA-Halle wurde durch die Beschaffung eines neuen 80 t Kranes mit passender Traverse (125 t Traglast + 5 t Eigengewicht) auf 130 t erhöht zur Montage und Installation der Testanordnung. Eine große Zahl von Vortests und Entwicklungs- und Anpaßarbeit waren erforderlich, um die Komponenten entsprechend den Anforderungen einsatzfähig zu machen, wozu als integrale Vortests auch der 1.8 K Test der EURATOM LCT-Spule und der Test der W 7-X Prototypspule zählen.

Abstract

In the frame of a contract between the ITER (International Thermonuclear Experimental Reactor) Director and the European Home Team Director was concluded the extension of the TOSKA facility of the Forschungszentrum Karlsruhe as test bed for the ITER toroidal field model coil (TFMC), one of the 7 large research and development projects of the ITER EDA (Engineering Design Activity). The report describes the work and development, which were performed together with industry to extend the existing components and add new components. In this frame a new 2 kW refrigerator were added to the TOSKA facility including the cold lines to the Helium dewar in the TOSKA experimental area. The measuring and control system as well as data acquisition was renewed according to the state-of-the-art. Two power supplies (30 kA, 50 kA) were switch in parallel across a Al bus bar system and combined with a 80 kA dump circuit. For the test of the TFMC in the background field of the EURATOM LCT coil a new 20 kA power supply were taken into operation with the existing 20 kA discharge circuit. Two forced flow cooled 80 kA current leads for the TFMC were developed. The total lifting capacity for loads in the TOSKA building was increased by a ordered new 80 t crane with a suitable cross head (125 t lifting capacity + 5 t net mass) to 130 t for assembling and installation of the test arrangement. Numerous pre-tests and development and adaptation work was required to make the components suitable for application. The 1.8 K test of the EURATOM LCT coil and the test of the W 7-X prototype coil count to these tests as overall pre-tests.

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3.1 Introduction

The reliable operation of the ITER superconducting magnet system is an indispensable necessity for a successful execution of the project.

As an intermediate development step in the construction of the ITER coils, model coils representative for the CS and TF coils will be manufactured and tested. This testing will be carried out in two facilities, at FZK in the EU and at JAERI in Japan. The test conditions must be representative of those in ITER, but at the same time the necessary modifications to the facilities must be kept to a minimum for the cost of the programme in order to be acceptable.

On the basis of existing equipment, the TOSKA facility of FZK Karlsruhe was selected for testing the toroidal field model coil (TFMC) [3.1-1]. In TOSKA, the typical weight of the model coil can be handled and cooled down in an existing sufficiently sized vacuum vessel. A completed cryogenic system supplies the magnet and its auxiliaries up to 2 kW refrigeration power at 4.2 K. The achievement of Lorentz force densities required for testing the electromechanical behaviour is assured by DC currents up to 80 kA as well as a suitable background field generated by the EU LCT coil. It was found during the model coil test definition work that the TF model coil test with overcurrent and in the background field of the existing LCT coil is the desirable scheme with reasonable costs for such a test.

After the change of the design of the ITER TF coils a rationale and a conceptual design was elaborated by the European Home Team (EUHT) and accepted by the Joint Central Team in February 1995. The race track shape TF model coil is tested in the background field of the LCT coil. A frame called intercoil structure supports the TF model coil and transmits the force to the LCT coil (Fig. 3.1-1). A summary of geometrical dimensions, field and forces is given in Table 3.1-1. The load lines under different operation conditions is given in Fig. 3.1-2 [3.1-2]. Minimum test requirements have been specified by the JCT in the request for task proposals, dated February 1st, 1993. The requirements as specified in chapter 3.1.1 and 3.2.2 of Annex A of this document can all be met by the TOSKA facility.

Table 3.1-1: Parameter of the TF model coil (RT: race track shape; Comment: In this table the filed calculations were performed by using an averaged current density. Therefore the field levels are lower than those given in Fig. 3.1-2)

ITER RT-Shaped Model Coil Test (Inclination of 4.5° to LCT)		
Parameter (April 1995)		**Vertical RT-98 turns x 70 kA** **LCT-588 turns x 16 kA**
Overall length of MC	m	3.792
Overall width of MC	m	2.706
Overall thickness of MC	m	0.773
Minimal bending radius	m	0.609 + 0.1 = 0.71
Radial winding thickness	m	0.537
Axial winding thickness	m	0.573
Length of straight section	m	1.1
Average turn length	m	8.35
Conductor length (without spare conductor)	m	818
Winding volume	m^3	2.57
Estimated weight	kg	18000
Operation temperature	K	3.5
Overall-current density in RT	kA/cm^2	2.2295 (active)
Current in RT coil	MA	6.86
Current in LCT conductor	kA	16
Current in LCT coil	MA	6.72 + 2.688 = 9.408
Attainable magnetic fields		**Region of bending (midplane)**
B_{max} at MC (self)	T	6.54 (5.7)
B_{max} at MC with LCT	T	8.75 (8.06)
B_{max} at LCT coil	T	9.04 (8.74)
Attainable resulting forces		
F_X at LCT	MN	12.77
F_Y at LCT	MN	70.4
Inductance of MC	H	0.0273
Stored self-energy of MC	MJ	67
Stored self-energy of LCT	MJ	200
Total stored energy (MC + LCT)	MJ	337

Table 3.1-2 Minimum requested and available capabilities

Comparison of minimum requested and available capabilities		
	minimum	available
Duty factor	0.33	0.42
Operating temperature	4.5 K	3.5 - 4.8 K
Total He flow rate for coil	250 g/s	≤ 500 g/s
Average AC loss in coil	50 W	50 W
Maximum pressure	7 bar	≤ 10 bar
Maximum pressure drop	4 bar	≤ 6 bar
Max. helium volume in coil	500 l	

Use of or addition to existing equipment extends the test conditions for the TF model coil. The following options can be provided. They have been recommended by the model coil working group and were approved by the JCT.

Option 1	Overcurrent up to 80 kA.
Option 2	The facility offers the possibility for testing the model coil adjacent to the EU LCT coil for generating out-of-plane forces.
Option 3	High voltage by fast discharge.

These options were approved by the ITER authorities in spring 1994 and included in the task agreement.

The TOSKA facility was extended in steps accompanied by overall tests proving the reliability and availability of the new installed components. The first work package was the extension of the basic components of the TOSKA facility including:

- The cryogenic and electrical supply system,
- The process control by instrumentation and data acquisition,
- The preparation of the LCT coil for a new load case,
- Load handling equipment.

This stage was successfully completed with tests of the LCT coil at 1.8 K.

In a second work package the facility has been prepared for the extension of the components which have been very specific related to specific design of the TF model coil and its test programme. Simultaneously, TOSKA must be prepared for a national obligation in the frame of the W 7-X stellarator project, namely the testing of the W 7-X prototype coil as a prerequisite for ordering the serial fabrication of the W 7-X torus coils. Unfortunately, the fabrication of the W 7-X prototype coil was running with substantial delay. Now the test of the W 7-X prototype was successfully completed in August 1999, and it was removed from the TOSKA vacuum vessel end of September 1999. The collision of both programs appearing some times in the past were compensated by some delays in the TFMC program caused by technical difficulties. In addition the configuration (test coil in the background field of the LCT coil) is used as well for the W 7-X prototype as for the TFMC. The structure fabrication and the assembly is performed by the same industrial partner performing this work for the TF model coil. Thus the experience gained with the W 7-X prototype coil should speed up the TF model coil assembly.

There have been achieved also results during testing of the W 7-X prototype coil which have to be assessed and taken into account for the TFMC test [3.1-3].

3.1.1 References

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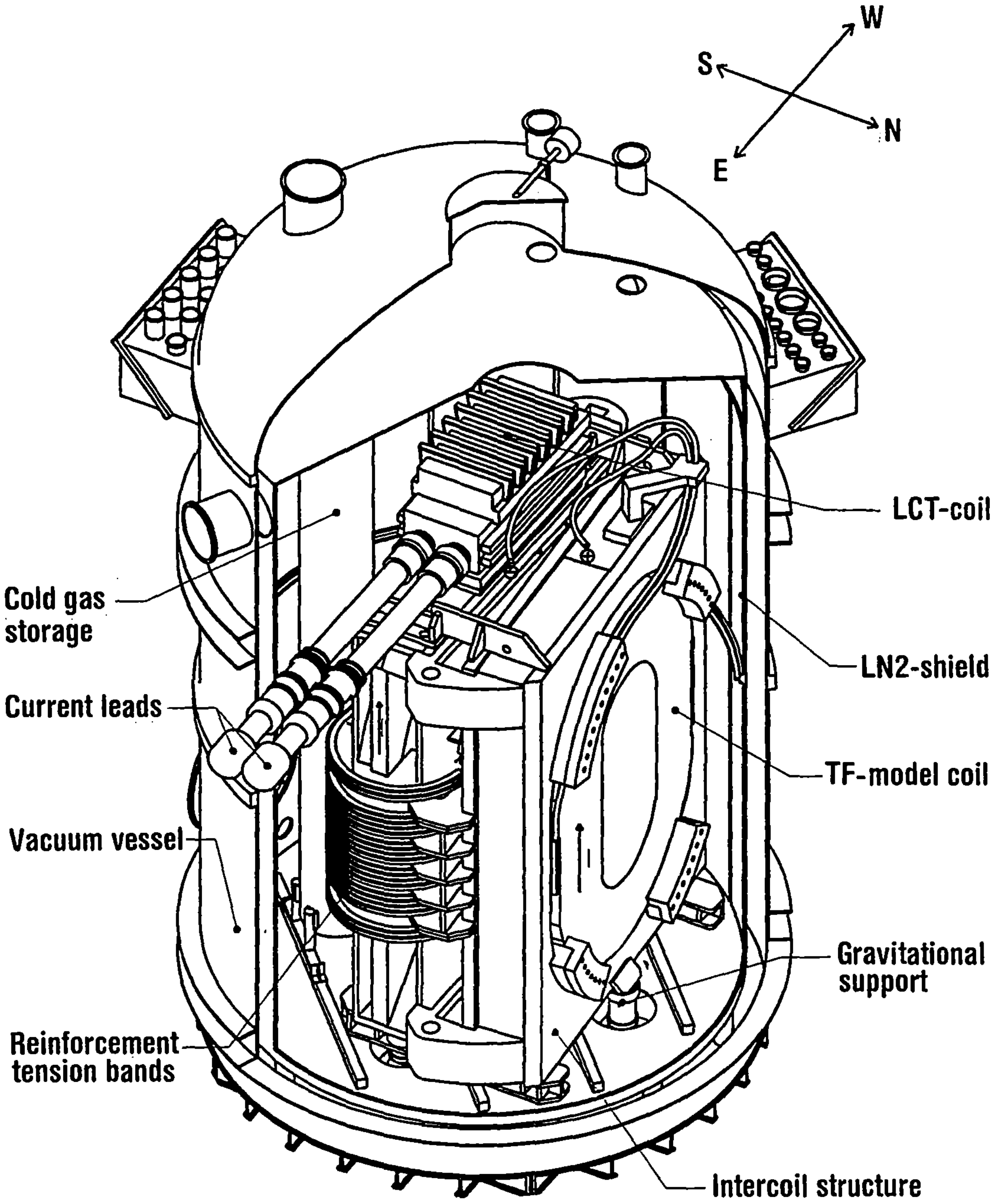

Fig. 3.1-1: Schematic view of the TOSKA vacuum vessel with the TFMC test configuration inside

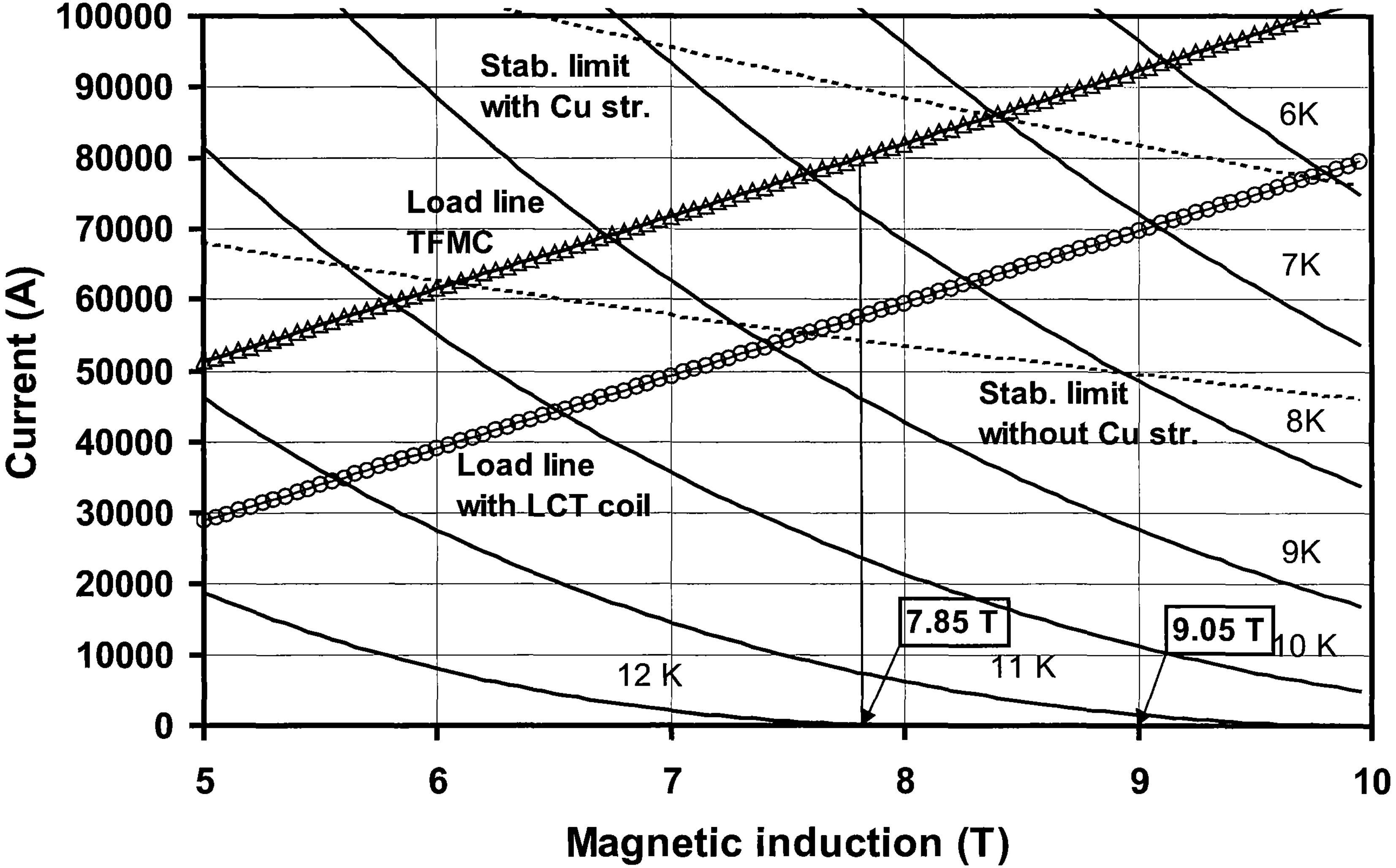

Fig. 3.1-2: The operating diagram of the TFMC alone and in the background field of the LCT coil

3.2 General Facility Description

3.2.1 Basic Facility Components

The TOSKA facility was constructed in the years 1980 - 1984 as a test facility for large superconducting magnets at the Research Center Karlsruhe (FZK). The first magnet tested in this facility was the Euratom LCT coil in spring 1984 starting the development of toroidal field coils for tokamaks [3.2.1-1]. The second test object was the POLO model coil. The typical features and suitable experimental testing methods were developed for tokamak poloidal field coils within this project [3.2.1-2]. In the frame of the EU technology programme, the facility was continuously upgraded in order to meet the specifications for testing model coils fabricated from the prototype conductor length of the superconducting magnets of the next large scale fusion machine. On the basis of this development, the facility is capable by some modifications and additions as a test facility for ITER model coils to reasonable costs.

The facility is operated by FZK, in the Institute for Technical Physics (FZK/ITP). The TOSKA facility and its auxiliaries are installed mainly in two neighbouring buildings. One is the refrigerator building, the other one contains the test bed for the magnets (Fig. 3.2.1-1).

The TOSKA facility consists of:

Building (test bed): 45 m length, 18.50 m width, 13 m height: floor-lower edge crane hook. Access to the experimental area by a door 10.80 m width, 12.55 m height

Vacuum vessel with nitrogen shield:

5 m outer diameter; height 8.70 m; usable test space 4.45 m ; height 6.6 m within LN_2 shield. The test configuration has to be within an envelope of 4.3 m diameter in order to have sufficient clearance to the LN_2 shield and its piping.

The vacuum vessel is sunk below ground level to reduce impact from magnetic fringing fields as much as possible (Fig. 3.2.1-2).

Cryogenic system

The TOSKA facility is supplied by two helium refrigerators (500 W and 2 kW) which are equipped with extended liquid storage dewars and warm gaseous storage capacities at low, medium and high pressure. The refrigerators are linked by a cold pipe system to the TOSKA facility where the cryostats are located for the pumps and heat exchangers driving the forced flow loops (Table 3.2-1). Fig. 3.2.1-3 gives the refrigeration versus liquefaction capacity and Fig. 3.2.1-4 presents the available cooling power for the cooldown of a magnet system. The valve and cold box in the refrigerator building is shown in Fig. 3.2.1-5.

Table 3.2-1: TOSKA cryogenic system

Specific 2 kW refrigerator	
Operating temperature range	3.5 - 4.5 K
Continuous cooling power at 4.4 K	2 kW
Cold pump circulating flow (excluding current leads)	500 g/s
General laboratory refrigerator	
Operating temperature range	1.8 - 4.4 K
Continuous cooling power	380 W at 1.8 K 500 W at 4.4 K

Electric power supplies

Two power supplies, one ±30 kA (bipolar) and the other +50 kA (unipolar), can be operated independently or in parallel up to 80 kA at a voltage of 30 V. An additional power supply (20 kA, 30 V) was installed for the LCT coil.

Crane

The existing cranes in the experimental area have a lifting capacity of 50 t and 80 t. They have a synchronous control system and control panel.

Process control measuring and data acquisition

After the completion of the POLO project, the complete measuring and control system of the TOSKA facility was modernized. The digital output of all electrical units (programmable logic controllers, PC's, workstations, sensor, scanners, CAMAC crates, controller, etc.) communicate with the process control system. It controls and monitors the complete system on the basis of the measured data. All data are stored in a data base. Operators can monitor the status of the system on the display and can adjust operation parameters by mouse click.

3.2.2 Specific components for the Model Coil Test

3.2.2.1 Gravitational support structure

Model coil adjacent to the LCT coil (Option 2):

The model coil, the LCT coil and the intercoil structure rest on three feet. One is integrated in the intercoil structure. Two feet support the LCT coil and have a gravitational support beam going to the intercoil structure (Fig. 3.1-1). The whole test rig is carried by three fibre glass cylinders resting on crossed roller bearings which allow shrinking of the test rig against the warm vacuum vessel bottom. The test configuration is elastically fixed by two times 4 horizontal rods against the wall of the vacuum vessel.

3.2.2.2 Vessel modifications

Model coil adjacent to the LCT coil (Option 2):

One additional port for current leads for the TF model coil was installed in the vacuum vessel wall. Also, one nitrogen shield panel had an additional penetration for one current lead of the TF model coil.

3.2.2.3 Superconducting busbars

Three kinds of busbars are needed for the execution of the task:
Busbar type I: Carrying the current between the winding terminals and busbar type II

Busbar type II: Carrying the current between the busbar type I and the cold end of the current lead.

Busbar type III: It will make a short circuit connection between the ends of the busbars type II for testing the current leads in a separate test

Model coil adjacent to LCT coil (Option 2)

Two long superconducting busbars type I and type II are needed to connect the winding terminals with the cold end of the current leads. For assembly reasons, an intermediate joint between busbar type I and II in the TOSKA vacuum vessel is indispensable. The joint at the coil side and the intermediate joint are performed in the pancake joint technique while the joint to the current leads needs a special terminal. The surprisingly high measured losses at the LCT current leads for horizontal installation position forced the change to a vertical installation position with this superconducting busbar system An extension of the TOSKA vacuum vessel is needed too(see section 3.3.4).

3.2.2.4 Diagnostic and control items

Model coil adjacent to the LCT coil (Option 2):

The existing diagnostic and control system was upgraded for fulfilling the requirements of a modern control and data acquisition system. To reduce the sensor number and the update time of calculated values, all programmable logic controllers were integrated in the computer system by a digital bus. The system contains a transient and continuous data recording. About 300 channels are required for the model coil.

About 200 channels for the LCT coil and 100 channels for the intercoil structure are needed additionally.

3.2.2.5 Resistors

Model coil adjacent to the LCT coil (Option 2):

The discharge resistors for the TF model coil are air cooled, insulated for 6 kV and have an adequate mass for dumping a stored energy of 0,1 GJ.

Resistors for the LCT coil exist.

3.2.2.6 Switch gear and busbars

Model coil adjacent to the LCT coil (Option 2):

The stored energy and discharge time constant permit the use of arc chute breakers. For redundancy reasons, three breakers are needed. The switches will be controlled by suitable programmable controllers with adequate redundancy and instrumentation.

The LCT switching circuit exists. Modifications for the synchronization of both circuits are not necessary according to the experience gained by the W 7-X prototype coil test.

3.2.2.7 Current leads

Model coil adjacent to the LCT coil (Option 2):

Two forced flow cooled current leads according to the design of the Polo current leads will be applied. They will be optimized for a current of 60 kA but also capable to be operated at a higher current of 80 kA with a still acceptable load for the refrigeration system.

Current leads for the LCT coil are available from the test of the W 7-X prototype coil. They are an improved version of the POLO current leads special for horizontal installation tested successfully in the W 7-X test.

3.2.2.8 Helium collection after quench

Model coil adjacent to the LCT coil (Option 2):

A 1.85 m^3 medium pressure (26 bar) cold storage vessel was sufficient for collecting the helium from the dumped LCT coil. The TF model coil helium volume will be comparable with that of the LCT coil (750 l). However, this item depends in detail on the test programme and quench analysis of the TF model coil and must therefore be re-evaluated in time. According to the existing experience (also confirmed in the test of the W 7-X prototype coil), the cold storage should be adequate for collection of quench gas without losses.

3.2.2.9 Crane and lifting gear

Model coil adjacent to the LCT coil (Option 2):

The limited space requires the installation of the model coil configuration into the vacuum vessel as one large unit. Therefore, a second crane bridge was installed. The maximum lifting capability with a suitable lifting gear is 130 t.

The lifting capability is estimated as sufficient to install the total test configuration with the model coil, the LCT coil, the gravitational support and intercoil structure.

3.2.2.10 Option 1: Overcurrent

For generating higher fields and forces, the capability of operating both power supplies (30 kA- and 50 kA-power supply) in parallel can be used to obtain 80 kA. Current leads are designed such that they are just causing for higher currents a larger load to the refrigerator. There are practical no extra costs as demonstrated by the POLO current lead experiment at FZK.

If the model coil should be operated at 80 kA and under out-of-plane forces, a power supply is needed for the LCT coil.

The main busbars have to be designed for 80 kA current carrying capacity.

3.2.2.11 Option 3: High voltage

The winding system consisting of conductors embedded in radial plates has to be investigated under transient voltages. The equivalent circuit which determines the behaviour of transient voltages is not evaluated and verified by experiments. Fast discharge of the inductive stored energy offers the possibility to investigate this item which belongs to the dielectric strength of a system as well as the dielectric strength of the insulation material.

Using a current of 25 kA which is adequate to create 10 kV by fast discharge the modified POLO counter acting current switch can be used [3.2.2.1-2]. Some busbars and the discharge resistor have to be modified for the higher stored energy.

The existing POLO switching circuit is also able to apply a repetitive discharge of a capacitor bank of 150 µF into an inductance up to 23 kV. This could provide an additional pulsed high voltage test.

Currents above 25 kA would need an expensive new switching system and are therefore no longer considered.

3.2.3 Status

The completion and commissioning date of the basic components of the TOSKA facility are summarized in Table 3.2.3-1.

Table 3.2.3-1 Commissioning and completion date of the basic facility

Component	Completed
- 2 kW refrigerator	June 1994
- Cold supply lines between 2 kW refrigerator and TOSKA with valve box	June 1995
- 80 t crane	May 1994
- 80 kA power supply	April 1995
- Measuring and control	May 1996
- Cryogenic supply system	May 1996
- Dump circuit for the LCT coil	May 1996
- Test of the LCT coil at 1.8 K up to 11 T and 19.6 kA	August 1996
- Overall test of the basic facility with the LCT coil	August 1996
- Test of W 7-X prototype coil as an intermediate testing step of the upgraded TOSKA facility	August 1999

The continuous testing while setting the facility components into operation delivered valuable information and necessary improvements for the test of the TF model coil. This will be described in the following sections.

Outstanding results were achieved with the LCT coil during the test at 1.8 K operation (Fig. 3.2.3-1).

The critical line followed exactly those derived from measured and extrapolated values from short sample strand measurements (Fig. 3.2.3-2) [3.2.3-1]. The detailed finite element analysis of the LCT coil and its reinforcement structure showed excellent agreement [3.2.3-2]. The stress levels are compatible to those which will be achieved in the test configuration of the TF model coil (Table 3.2.3-2).

Table 3.2.3-2 : Stress levels achieved in the test of the LCT coil at 1.8 K compared with the stress levels during testing in the TFMC configuration (TF model coil, + intercoil structure + LCT coil).

Winding

	Test parameter TFMC 80 kA LCT 16 kA Partly reinforced ICS Design [3.2.3-3]	Test parameter LCT 1.8 K 19.6 kA Reinforced [3.2.3-4]	Maximum allowable stresses
$\sigma(r)$	- 43 MPa	- 40 MPa	- 300 MPa
$\sigma(\varphi)$	187 MPa	257 MPa	300 MPa
$\sigma(z)$	- 280 MPa	- 48 MPa	- 300 MPa
$\lvert\tau_{shear}\rvert$	45 MPa	38 MPa	50 MPa

Coil case

	Test parameter TFMC 80 kA LCT 16 kA Partly reinforced ICS Design [3.2.3-3]	Test parameter LCT 1.8 K 19.6 kA Reinforced	Maximum allowable stresses
$\sigma_{\text{von Mises}}$	567 MPa	521 MPa [3.2.3-5]	700 MPa [3.2.3-5]

The status at facility components specific for the TF model coil are summarized in Table 3.2.3-3.

Table 3.2.3-3: Status of the facility components specific to the TF model coil

Component	Status
- Gravitational support	Completed
- Instrumentation, measuring and control (process scheme)	Commissioning completed as far as possible without TFMC
- 80 kA TF model coil dump circuit including dump resistor	Commissioning completed up to 10 kA dumps
- 80 kA currents leads	Assembling completed
- Cryogenic supply of the TFMC and cold helium recovery (process scheme)	Commissioning completed as far as possible without TFMC
- Cryostat extension	Commissioning completed as far as possible without mounted current lead
- Lifting gear 125 t	Commissioning completed
- 20 kA power supply for LCT coil	Commissioning completed
- POLO switching circuit modification	No modification necessary

The 80 kA dump circuit, 80 kA current lead and 20 kA power supply are special components. The 80 kA current leads have been developed. Several problems occurred and were successfully mastered (section 3.3.4). The 80 kA dump circuit was a new current range level never built before but it could be composed from industrially available components. The actual test during commissioning showed the necessity of some improvements (section 3.4.3). The 20 kA power supply and 80 kA dump circuit were considerably more expensive than expected and needed special efforts for making resources available and getting approval.

For getting test results of the TFMC before the end of the ITER EDA it was decided by the Association Steering Committee to split up the test in two phases:

Phase I: Test of the TFMC as single coil

Phase II: Test of the TFMC with the LCT coil

This splitting reduces the installation time and the risk of faults which can lead to further delays.

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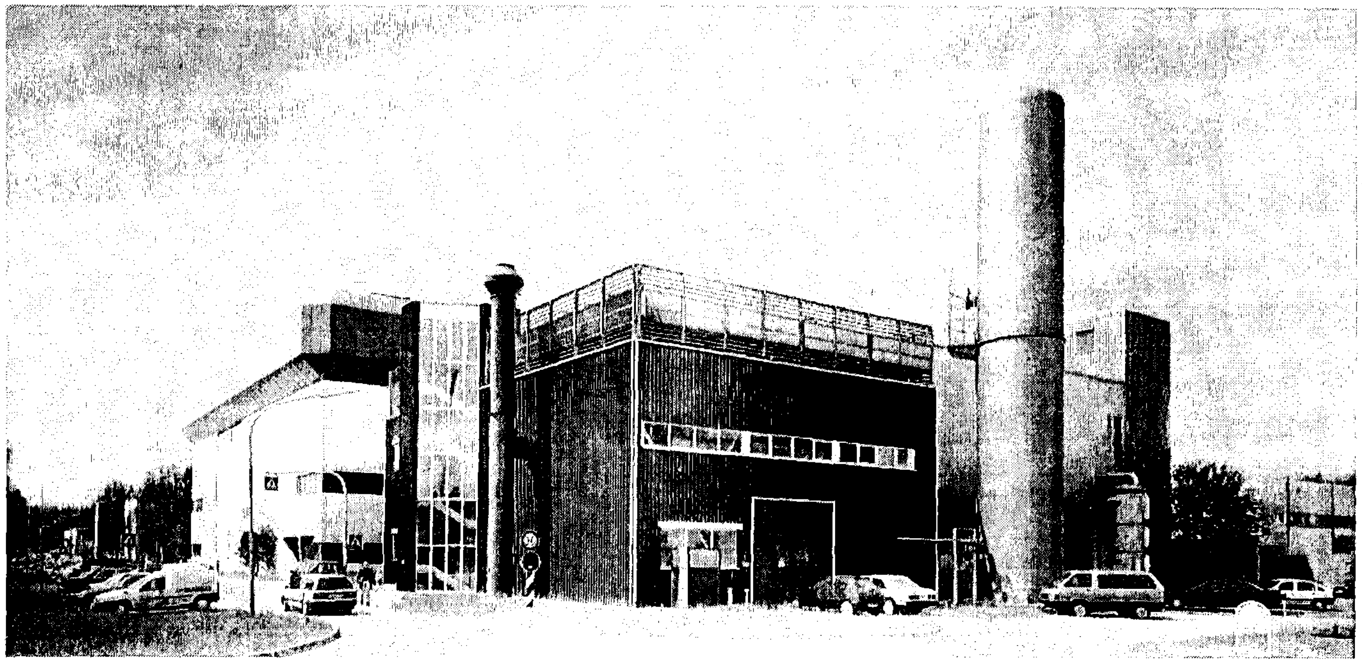

Fig. 3.2.1-1: Buildings of the TOSKA facility. In front the refrigerator building for the 2 kW refrigerator and a medium pressure helium gas storage is seen. In background, the building is shown where the test bed is located.

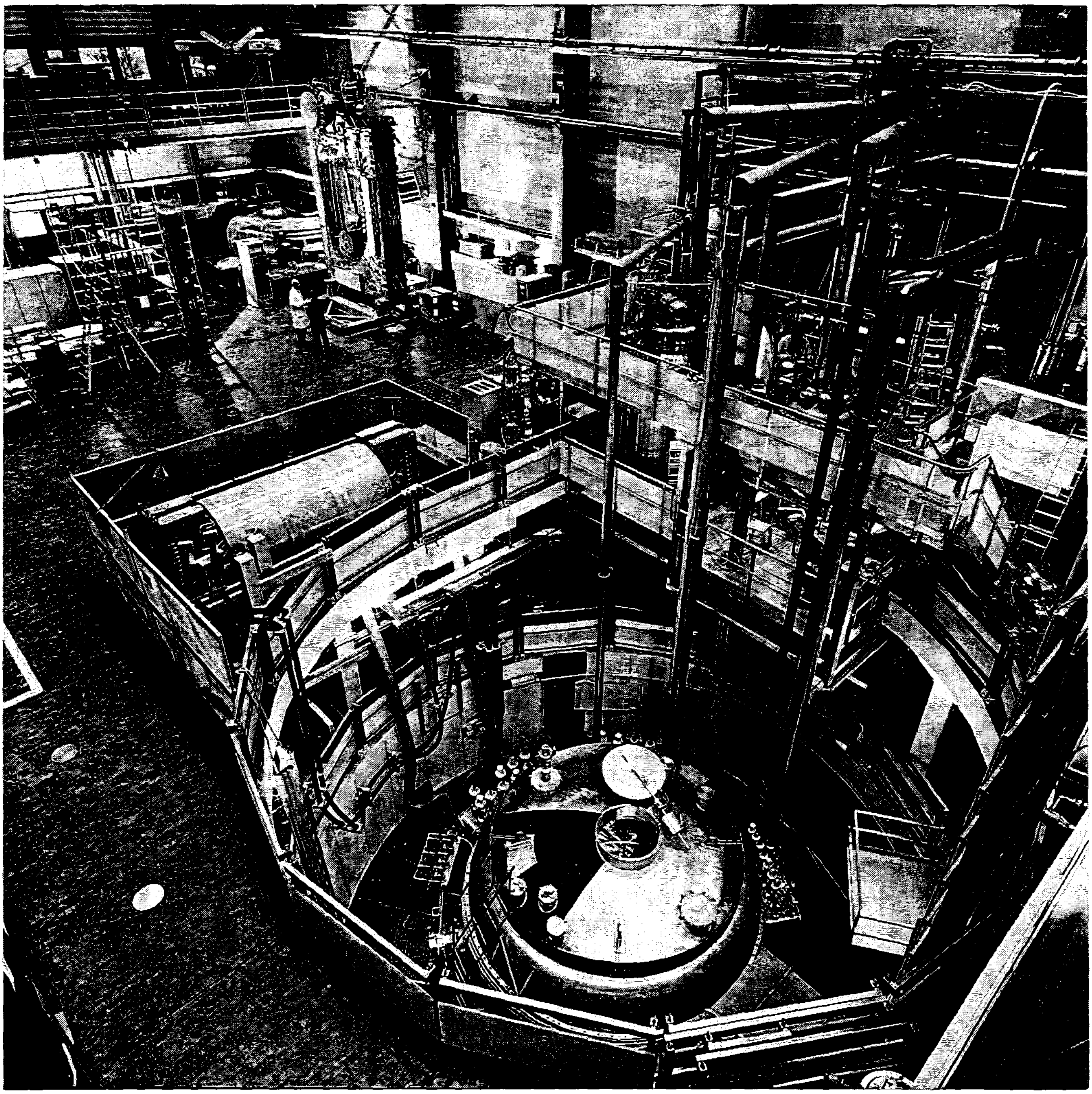

Fig. 3.2.1-2: A glance of the experimental area of the TOSKA facility with the vacuum vessel, the cold helium line system and the LCT coil in background (1988)

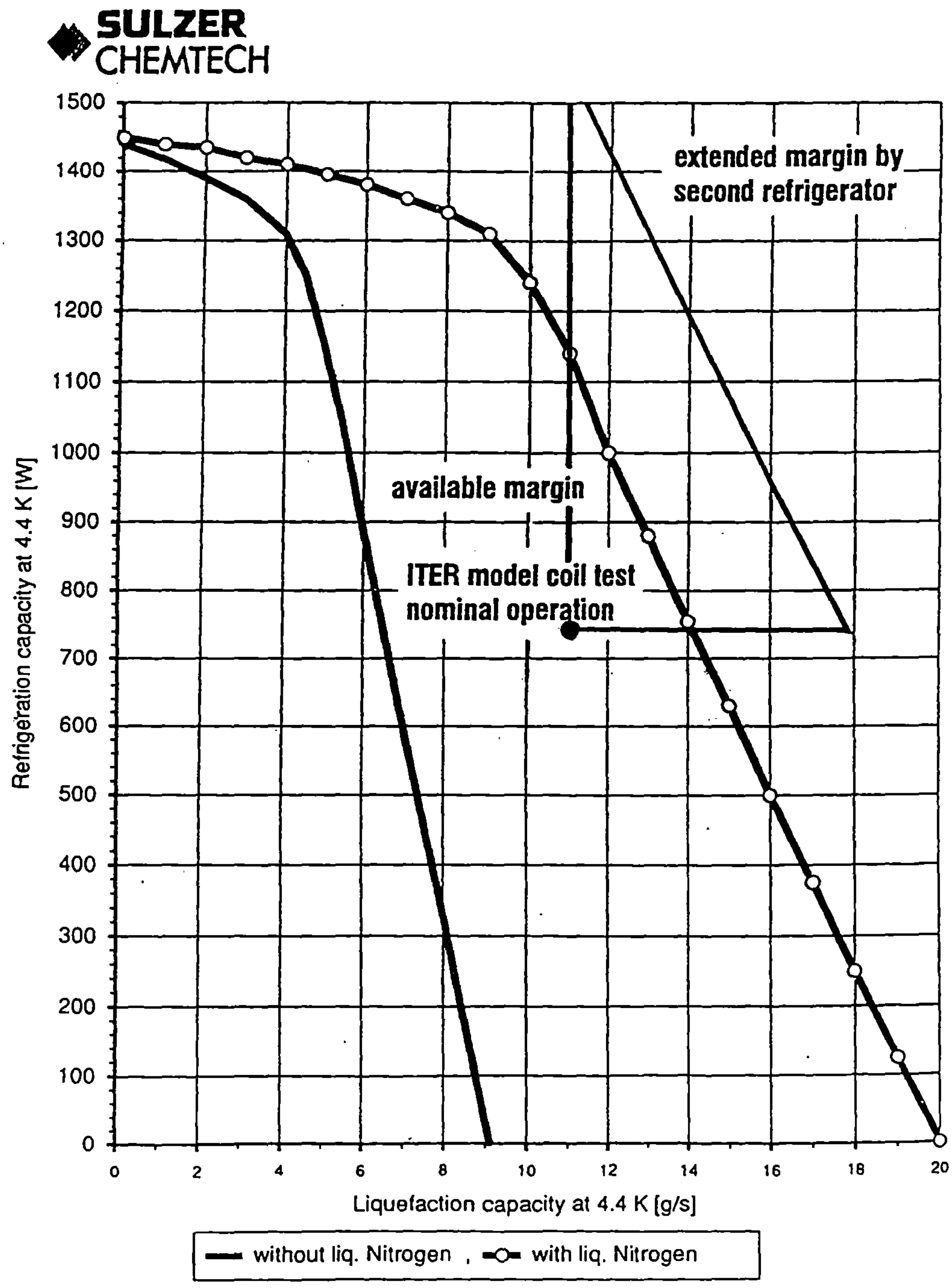

Fig. 3.2.1-3: Refrigeration versus liquefaction capacity of the 2 kW helium refrigerator

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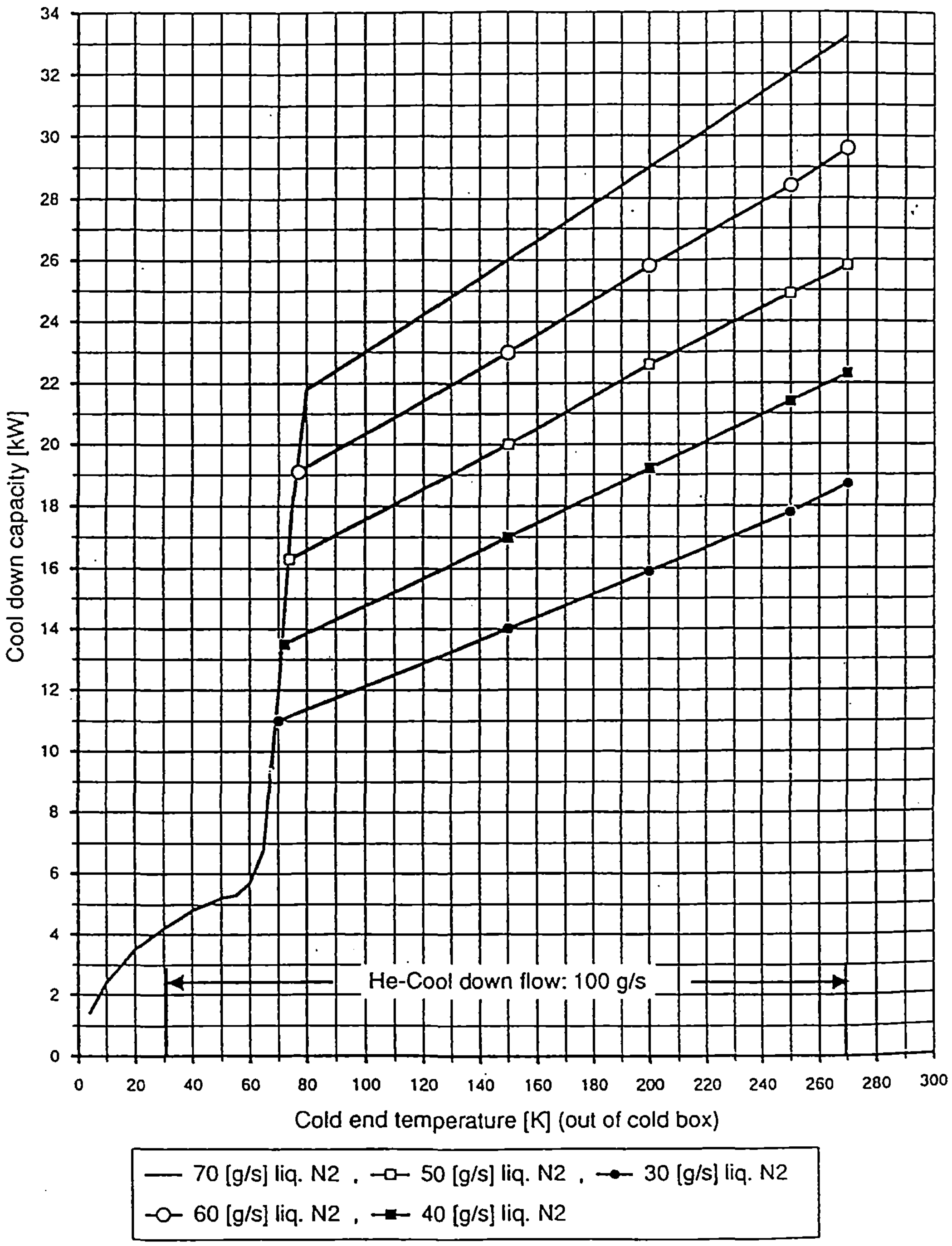

Fig. 3.2.1-4: The available cooling power for cooldown the magnet system using nitrogen for pre-cooling

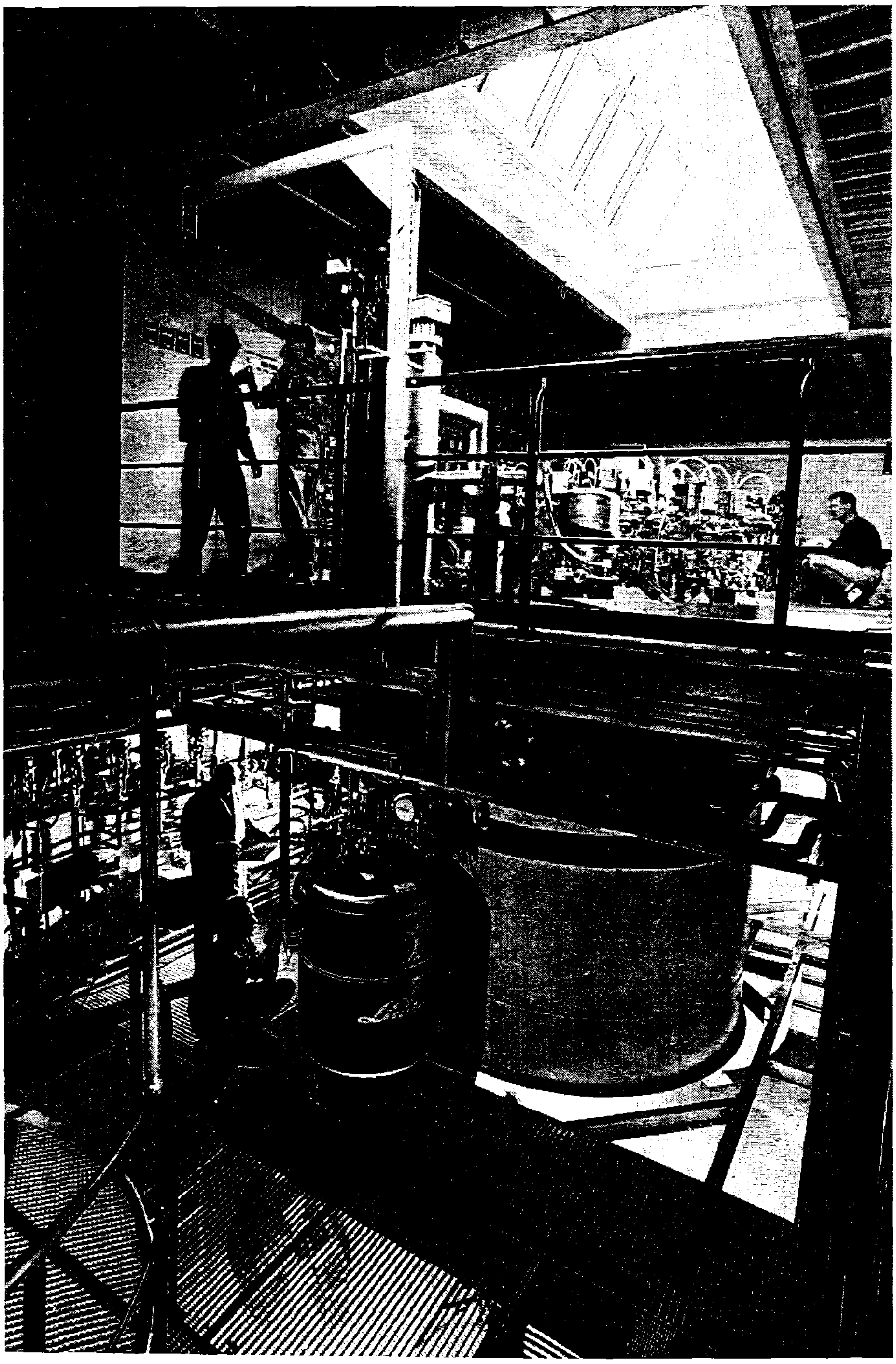

Fig. 3.2.1-5: The valve box in front and the cold box in background during commissioning testing

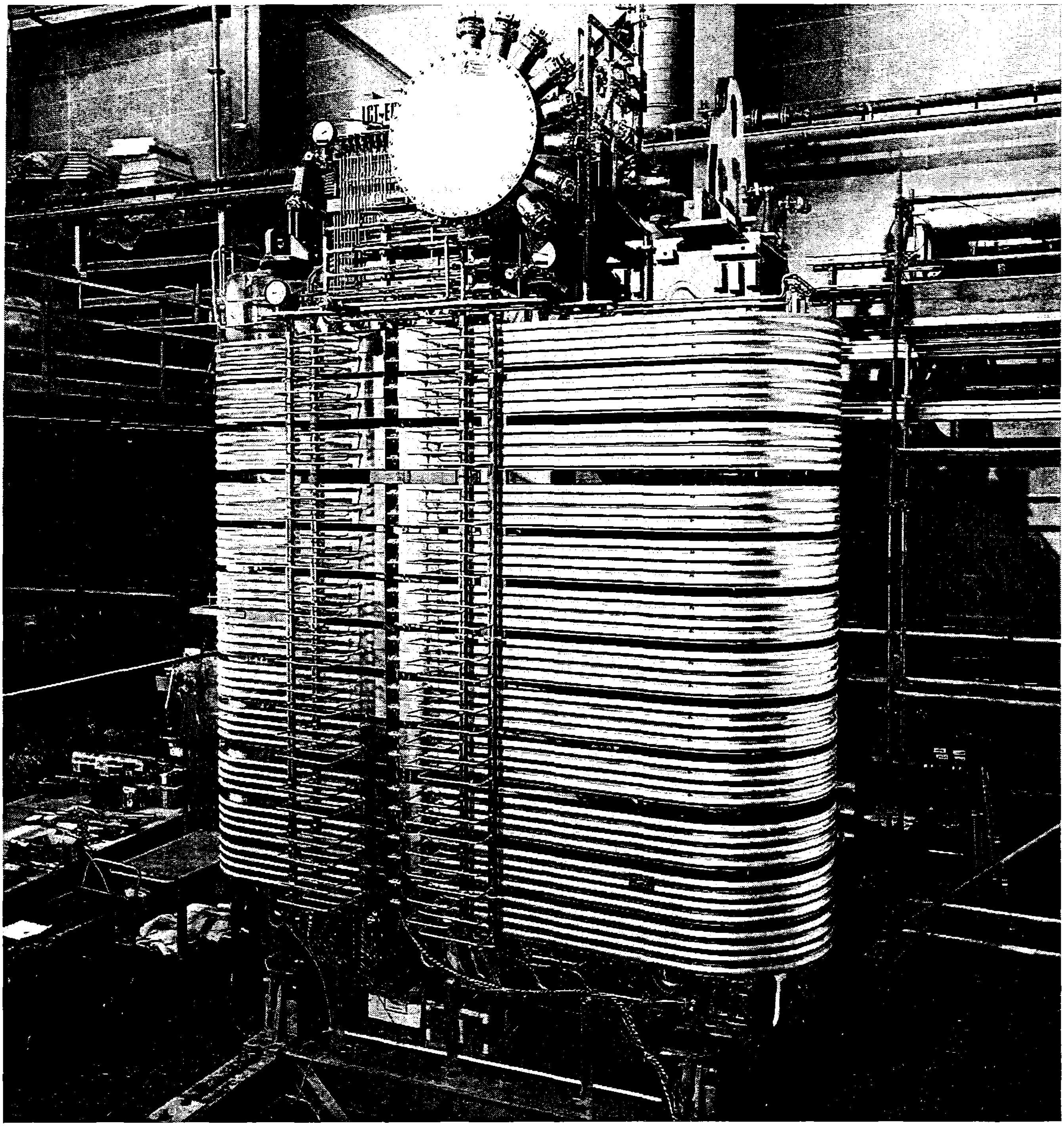

Fig. 3.2.3-1: The reinforced LCT coil prepared for the test at 1.8 K as single coil

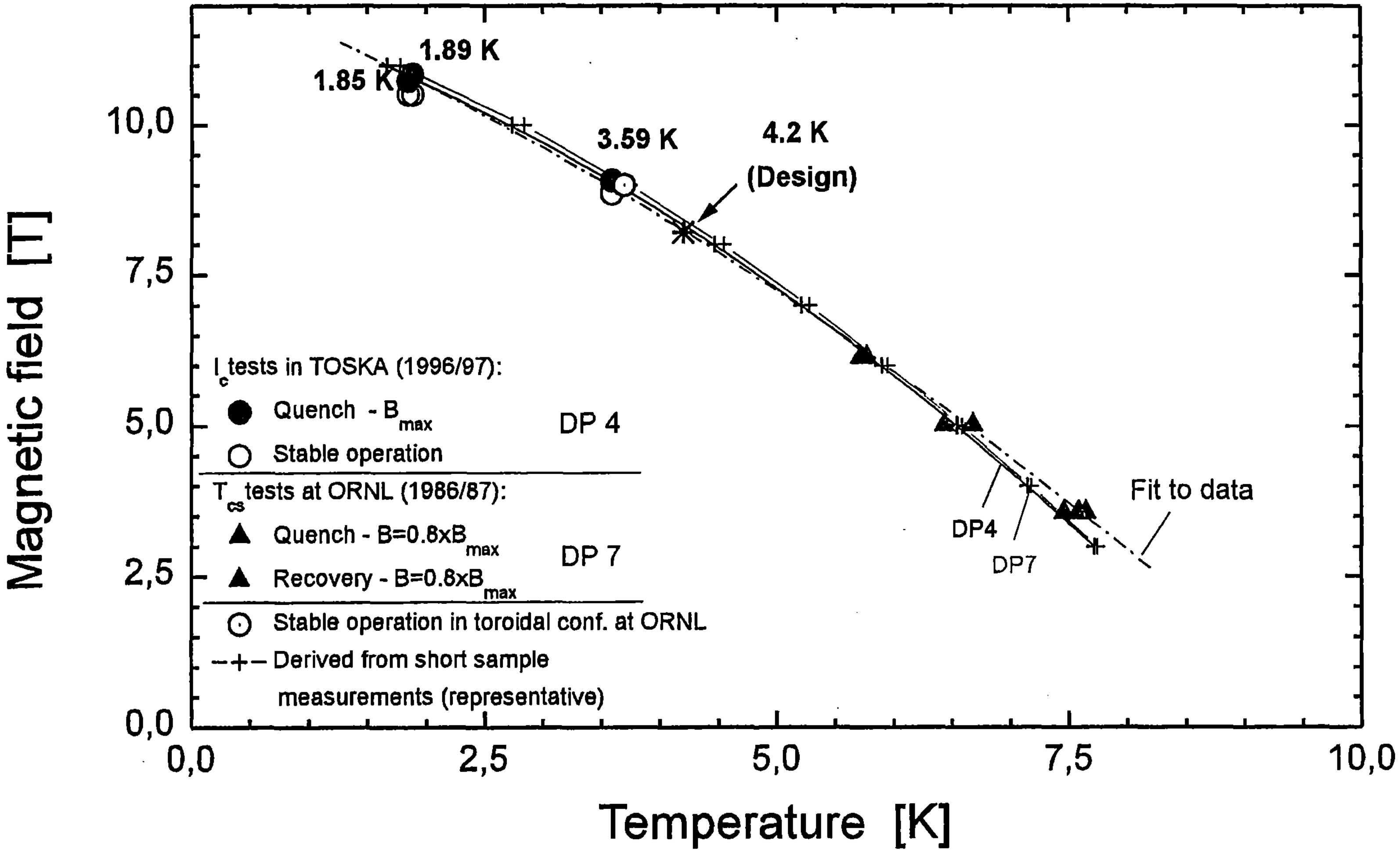

Fig. 3.2.3-2: The critical line of the LCT coil derived from strand measurements and measured quench currents for the LCT coil in the B vs. T graph

3.3 Cryogenic supply system

3.3.1 General description, overview

The TOSKA facility and the test coils are cooled by two refrigerators with nominal cryogenic power earlier presented in Table 3.2-1. Liquid nitrogen (LN_2) is supplied by a 100.000 l dewar and cools the radiation shields of the liquid helium dewars and the cold helium lines. Pre-cooling of the helium in the 2 kW refrigerator increases the cooling power (Table 3.2-1). The cold helium gas at 5 K to 6 K runs through cold lines to the TOSKA facility (Fig. 3.3.1-1, Fig. 3.3.1-2, Fig. 3.3.1-3.). The cold pressurized helium is expanded by a Joule Thomson valve and liquefied in the dewar B250. In a similar way, the dewar B1000 is supplied by a 0.5 kW laboratory refrigerator. Helium pumps and heat exchangers are emerged in the liquid helium bath of the dewars and circulate the helium mass flow through the superconducting magnet (Fig. 3.3.1-4). The helium in the forced flow circuit is kept at a supercritical pressure level (critical pressure 0.22 MPa) while the liquid helium in the dewar is kept slightly above or below the atmospheric pressure to achieve the desired operation temperature range for forced flow cooled magnets. For the 0.5 kW refrigerator, the pressure level can be lowered down to 1.6 kPa which correspondents to a helium temperature of 1.8 K. Beneath 2.2 K, helium is in its superfluid state with a different physical behaviour. The so called „Fountain effect“ can be used to construct a so-called „Thermomechanical pump“ which circulates helium without moving parts (Fig. 3.3.1-4).

Besides the main forced flow circuit described, a rather complex cooling system is needed for the operation of large superconducting magnets. This has to master all operation modes, e.g., controlled cooldown and warm up, test and standby operation as well as all fault conditions without any damage to the system. For example, pressure pulses like they occur during dumping of the magnetic energy are mastered by two pressure levels (pressure release by a pressure controller to a cold gas storage for intermediate storage in a pressure vessel). Under normal test operation, the system is designed to release no helium into the atmosphere. Unexpected heavy fault conditions force the release of helium gas through safety valves and burst disks to the atmosphere. For all fault conditions, e.g., electrical power outage, the system passes over into a safe mode where the system can remain unattended without damage.

The cooling system is controlled by numerous sensors, controllers, programmable logic controllers (PLC) and a process guiding system „VXL“ and monitored on displays. All data are stored in the data base „ORACLE“ and are available with a suitable software (ORIGIN 5.0) for numerical and graphic displays and evaluation.

3.3.2 Supply system for the LCT coil and the ITER TF model coil

The TOSKA facility is connected to the 2 kW-refrigerator by two separate cold transfer lines. One line is used for the cooldown of the test configuration (TFMC single coil test Fig. 3.3.2.-1, TFMC coil with LCT coil test Fig. 3.3.2.-2) and the other for filling and supply of the control dewar. The advantage of these different lines is that the control dewar (B250) can be filled during the cooldown of the test rig and the forced flow operation of the coil can be started immediately by the pump circuit to reach the operation temperature of 4.5 K. A third line connects the laboratory refrigerator with a second control dewar (B1000) which was used for the 1.8 K test of the LCT coil. This system is still connected for allowing the cooling of the LCT winding at 3.5 K and the TFMC at 4.5 K. The possible cooling operation scenarios are presented in Tab. 3.3.2-1.

Table 3.3.2-1: Operation scenarios for the TFMC configuration

TFMC		LCT		Notes
I [kA]	T [K]	I [kA]	T [K]	**Refrigerators used**
70	4.5	12	4.5	2 kW only
70	4.5	16	3.5	2 kW and 0.5 kW
70	3.5	16	3.5	2 kW only (time limit)
80	4.5	-	-	2 kW only, without LCT

3.3.2.1 Controlled cooldown of the test configuration

A cold He mass flow rate of 100 g/s is available for the cooldown of the test configuration with a controlled temperature between 300 K and 10 K by the 2 kW refrigerator. For the controlled cooldown, all the readings of temperatures are checked for the warmest value by the control and visualization system; from this value the maximal allowed temperature difference across the coil is subtracted and used as set point for the controller. During the cooldown all components are cooled in parallel (Fig. 3.3.2.1-1) in order to reduce the temperature differences between the components. A selection of a relevant sensor and a temperature difference input is possible in the panel Fig. 3.3.2.1-2.

During the 1.8 K test of the LCT coil (Fig. 3.3.2.1-3) and the W 7-X coil , a smooth cooldown was achieved. The same system was used also for a controlled warm up.

The same procedure will be applied for the TFMC test.

3.3.2.2 Forced flow cooling of the test configuration with the pump circuit

After the cooldown, the test rig is cooled with supercritical He at a pressure of 3.5 bar, and the He is circulated by two piston pumps in the control dewar. This cooling mode has the advantage that the mass flow rate is independent from the mass flow rate of the refrigerator and disturbances from the coils during quenching and dumping have no influence on the refrigerator.

The He mass flow rate in this circuit is controlled by the revolution number of the pumps and distributed to the different cooling channels by valves. During the test of the LCT coil, winding, case and reinforcement structure were cooled in parallel with a stable mass flow. The mass flow rates are shown during energizing and dumping of the coil in Fig. 3.3.2.2-1.

For testing of the TFMC with LCT coil, the winding (TFMC + LCT), coil case and ICS will be cooled in series in order to reduce the overall mass flow rate and make best use of the He enthalpy (Fig. 3.3.2.2-2). During a simultaneous test of both pumps, the required flow rate was reached Fig. 3.3.2.2-3.

In Table 3.3.2.2-1and Table 3.3.2.2-2 the heat load to the cryogenic system during testing of the TFMC without and with LCT coil is summarized.

Table 3.3.2.2-1: Heat load for the cryogenic system during the TFMC test without LCT coil

	required for the TFMC configuration	available at the specific 2 kW refrigerator	required for the LCT coil at 16 kA	available at the general laboratory refrigerator
Winding			at 3.5 K	at 3.5 K / 4.5 K
Mass flow rate				
(ITER TFMC10 x 18 g/s	180,00 g/s	500 g/s		50 g/s
TFMC bus-bars	36,00 g/s			
LCT coil	0,00 g/s		50 g/s	
Operating pressure	3,50 bar	<10 bar	3.5 bar	<20 bar
Pressure drop (m=18g/s, Di=10mm, L=100m)	0,30 bar	6 bar	0.3 bar	6 bar
Pumping power (η= 0.6)	90,00 W		20 W	
Heat load sc-joints at TFMC coil (9 x2 x 10^{-9} Ω)	116,00 W			
Heat load sc-joints of bus bars (4 x 4.5 x 10^{-9} Ω)	116,00 W			
Radiation and conduction to coil	80,00 W			
AC-losses	50,00 W			
Case and support structure				
Heat input	100,00 W			
Mass flow rate (in series with winding)	270,00 g/s			
Current leads				
Nominal current TFMC	80,00 kA			
Warmgas flow rate TFMC(2 x 80 kA)	9,00 g/s			
Heat load joints TFMC (2 x 3.6 x 10^{-9} Ω)	46,00 W			
Nominal current LCT	0,00 kA			
Warmgas flow rate LCT (2 x 16 kA)	0,00 g/s			
Heat load joints of the LCT (4 x 2 x 10^{-9} Ω,)	0,00 W			
Facility				
Heat load in dewar, transfer lines, valves etc.	200,00 W		160 W	
Total refrigeration capacity at 4.4 K and 3.5 K	**798,00 W**	**1000 W**	**180 W**	**300 W / 500 W**
Total liquefaction capacity at 4.4 K	**9,00 g/s**	**12 g/s**		
Available margin	**202,00 W**		**120 W**	

Table 3.3.2.2-2: Heat load for the cryogenic system during the TFMC test with LCT coil

	required for the TFMC configuration	available at the specific 2 kW refrigerator	required for the LCT coil at 16 kA	available at the general laboratory refrigerator
Winding			at 3.5 K	at 3.5 K / 4.5 K
Mass flow rate				
(ITER TFMC10 x 18 g/s	180,00 g/s	500 g/s		50 g/s
TFMC bus-bars	36,00 g/s			
LCT coil	50,00 g/s		50 g/s	
Operating pressure	3,50 bar	<10 bar	3.5 bar	<20 bar
Pressure drop (m=18g/s, Di=10mm, L=100m)	0,30 bar	6 bar	0.3 bar	6 bar
Pumping power (η= 0.6)	100,00 W		20 W	
Heat load sc-joints at TFMC coil (9 x2 x 10^{-9} Ω)	116,00 W			
Heat load sc-joints of bus bars (4 x 4.5 x 10^{-9} Ω)	116,00 W			
Radiation and conduction to bove coils	100,00 W			
AC-losses	50,00 W			
Case and support structure				
Heat input	100,00 W			
Mass flow rate (in series with winding)	270,00 g/s			
Current leads				
Nominal current TFMC	80,00 kA			
Warmgas flow rate TFMC(2 x 80 kA)	9,00 g/s			
Heat load joints TFMC (2 x 3.6 x 10^{-9} Ω)	46,00 W			
Nominal current LCT	16,00 kA			
Warmgas flow rate LCT (2 x 16 kA)	3,00 g/s			
Heat load joints of the LCT (4 x 2 x 10^{-9} Ω,)	5,00 W			
Facility				
Heat load in dewar, transfer lines, valves etc.	200,00 W		160 W	
Total refrigeration capacity at 4.4 K and 3.5 K	**833,00 W**	**1000 W**	**180 W**	**300 W / 500 W**
Total liquefaction capacity at 4.4 K	**12,00 g/s**	**12 g/s**		
Available margin	**167,00 W**		**120 W**	

3.3.3 Helium recovery system

In case of a quench or a dump above a certain stored energy level (during the LCT test 14.5 kA), the valves from the coils to the control dewar (B250, B1000) are closed, and the pumps are switched off in order to separate control dewar and refrigerator system from the coils and to avoid a pressure or heat pulse to the supply system. The helium coming from the winding, case and ICS can be stored in a cold (77 K) vessel (Fig. 3.3.3-1) up to a pressure level of 18 bar, later on slowly warmed up to room temperature in a helium/water heat exchanger and fed into the gasometer. Up to now, all quenches and dumps were handled without losses of He. Only in case of an unexpected disturbance, helium will be relieved by valves or burst disks to the atmosphere. Both tests of the LCT coil and the test of the W 7-X prototype coil served as an excellent commissioning of all installed components of the TOSKA facility.

3.3.4 Current leads for TFMC

Two forced flow cooled current leads according to the design of the 30 kA POLO current leads are being assembled. The design principles as well as the performance of the POLO leads were presented in [3.3.4-1]. They will be capable to carry 80 kA with a still acceptable helium mass flow rate and heat load for the refrigeration system [3.3.4-2].

A schematic view is presented in Figure 3.3.4-1. One current lead consists of:

- a cold end made of electrolytic copper to reduce the Joule heating in the contact area which serves as the clamp connection part for the joint;
- a heat exchanger made of a central phosphorous deoxidized copper conductor surrounded by perforated copper plates brazed to the central conductor acting as heat exchanging part;
- to reduce the Joule heating of the joint and to be able to operate the current lead with minimum helium mass flow, Nb_3Sn inserts are introduced into the current carrying copper conductor.

- a flexible busbar cooled by high pressurized water to form the connection to the Al busbars of the power supply system;

The final detailed design of the 80 kA current lead is presented in Fig. 3.3.4.2-2

For the 1.8 K test of the LCT coil, two of the 30 kA current leads used for the POLO model coil test were installed horizontally because the use of forced flow supercritical helium for cooling the current leads allows an operation being independent on the orientation of the leads with respect to gravity. But during the test of the LCT coil, it was found that it was very difficult to operate the current leads in a stable way and, moreover, the helium mass flow rate needed to cool the leads were up to a factor of two higher than needed for the same leads installed in vertical position. In Figure 3.3.4-3, the helium mass flow rate needed to operate the current leads in a stable way is plotted as a function of the current both for vertical and horizontal installation. The consequence was that the orientation of the 80 kA current leads for the operation of the TFMC was changed from horizontal to vertical position. This requires a second busbar and an extension of two flanges of the TOSKA vacuum vessel but simplifies the construction with respect to mounting the leads in the vessel. Figure 3.3.4-4 shows the vertical installation of the 80 kA current leads in the TOSKA vacuum vessel with the supporting system of the busbar type II in the cryostat extension and the warm water cooled flexible busbars.

3.3.4.1 Current lead cold end

To reduce the resistance of the clamp contact, electrolytic copper is used in this region instead of phosphorous deoxidized copper because of the much lower electrical resistivity at low temperatures. Both copper parts will be brazed at the lower end of the heat exchanger. There are two types of busbars: busbar type I denotes the connection between the coil terminal to the intermediate joint in the vacuum vessel, and busbar type II identifies the connection between the intermediate joint and the current lead terminal. Figure 3.3.4.1-1 shows a cross sectional view of the contact area as realized in the LCT 1.8 K test whereas in Figure 3.3.4.1-2, the terminal of the type II busbar of the TFMC is given including the radial insulation break and the piping of the helium supply. According to an investigation the clamping system had to be reinforced to achieve a contact pressure of 20 MPa [3.3.4.1-1]. This was indispensable for getting a contact resistance in the nΩ range for making the heat load to the refrigerator acceptable. The clamping system was assured by a FEM calculation [3.3.4.1-2]. The routing of the type I and type II busbars according to the design of the European Industry Consortium AGAN represents Fig. 3.3.4.1-3.

3.3.4.2 Heat exchanger

The heat exchanger of the 80 kA current leads is designed with some modifications (hole diameter in the cooling fines reduced from 1.5 mm to 1 mm, meandering gas flow through the heat exchanger) as done for the 30 kA leads of the POLO model coil. To enlarge the thermal capacity of the lead a central conductor made of phosphorous deoxidized copper is surrounded by perforated copper plates made of electrolytic copper which are brazed to the central conductor. The perforations are modified according to the performance of the 30 kA current leads during the 1.8 K test of the LCT coil to get higher pressure drop respectively higher Reynolds number.

During brazing procedure a leak appeared in the weld seam between electrolytic copper cold end and the phosphorous deoxidized copper. The brazing material of the Nb_3Sn inserts run out till to the weld seam. This was confirmed by an ultrasonic inspection later on. The brazing material blocked at several sections near the intermediate flanges with the compensation bellows partly the cooling fins. This leads to an unacceptable high pressure drop. The blockage was localized by a pressure drop measurement at each section across the heat exchanger. The outer shell of the heat exchanger was opened near the flanges and the blocked cooling fins were partly removed by milling. The pressure drop measurements were repeated as long as all blockages were removed. Finally for both heat exchangers 0.2 MPa pressure drop was achieved at a mass flow rate of 5 g/s which is needed for operation.

3.3.4.3 Superconductor inserts at the current lead cold end

One design feature of the FZK forced-flow cooled current leads is the use of so called superconductor inserts in the joint region and to a large extend in the heat exchanger region. The reason to use Nb_3Sn as superconductor material was the high critical temperature of 10 - 12 K (at local magnetic fields) which allows to adjust the normal conducting length of the current lead according to operation current and helium mass flow rate which results in an optimized operation in a wide current range [3.3.4.3-1].

During the design phase of the 80 kA current leads, it was found that, due to space restrictions, it was not possible to extrapolate the margin of the superconductor inserts from 30 kA (POLO leads) to 80 kA. Therefore a series of measurements were done to characterize the performance of the superconductor strands which were industrially available. Internally copper stabilized Nb_3Sn strands were used because of the absence of a barrier between the copper of the current lead conductor and the superconductor filaments. A high current density strand made by VAC was found to be the most suitable one with respect to critical current. But afterwards, it was found that the interior construction of the strand led to bonding problems between the current lead copper and the strand itself. Measurements performed by embedding a strand which was also made by VAC and was used in the 30 kA POLO current leads in a copper profile showed that these strands can be used for the 80 kA current leads, too. In Figure 3.3.4.3-1, the quench current of the two selected strands embedded in copper profiles is plotted as a function of applied magnetic field. In Table 3.3.4.3-1, the measured quench currents of the different samples as well as the extrapolated numbers for the operation of the current leads are summarized.

The leak in the weld seam with the loss of the brazing material for the Nb_3Sn inserts required a repair. The copper material of the contact surface was removed by a special milling procedure and peeling. New copper profiles were soft soldered on the Nb_3Sn inserts by a Sn(50)In(50) melting at low temperature (~120 ^{0}C). The method was qualified by a series of trial soldering for achieving a good quality of solder filling in the gap between copper profile and Nb_3Sn inserts.

Finally the copper contact surface was gold coated for avoiding an oxide layer.

Table 3.3.4.3-1: Results of the extrapolation of the critical currents for the four test samples

No.	Sample	I_Q at 1.31 T, 4.2 K	I_{limit} at 1.31 T, 10 K
1	NS-13000(HP) in E-copper	3180 A	159 kA
2	NS-13000(HP) in SF-copper	2902 A	145 kA
3	NS-10000 in E-copper	2014 A	100 kA
4	NS-10000 in SF-copper	2031 A	102 kA

A detailed description of the measurement programme is given in [3.3.4.3-2].

3.3.4.4 Water cooled flexible busbar

During the design of the 80 kA current lead, it was found that one critical issue has been the warm end of the current lead even at high currents. Because of the much higher thermal capacity of pressurized water at room temperature instead of helium gas, the use of a water heat exchanger was envisaged. A second problem was the connection between the current lead and the water cooled Al busbars because the conventional available flexible water cooled cables required too much space for the connection to the current lead. So, a special high current density water cooled flexible copper piece was designed which could be integrated to the helium heat exchanger of the current lead. Test measurements done on a prototype model of this flexible busbar showed that an operation current of 80 kA could be carried stable without any overheating. Figure 3.3.4.4-1 shows a view of the components of the flexible busbar whereas in Figure 3.3.4.4-2 the prototype test configuration connected to the Al busbars is presented. In Figure 3.3.4.4-3, the operation current and inlet and outlet temperatures as measured during the test of the prototype is plotted as a function of time. A current density of 45 A/mm^2 was achieved.

3.3.5 System commissioning

Besides the acceptance tests of components of the system like measuring and control as well as data acquisition, two test series with the LCT coil and the test of the W 7-X prototype coil had to be considered as the overall commissioning test of the basic facility as specified in section 3.2.3.

- The 2 kW refrigerator worked reliable together with the TOSKA cryogenic supply system under real test conditions.
- The measured cryogenic power were in agreement with the refrigerator characteristic (Fig. 3.3.5-1).
- The necessity for changing the installation position is impressively demonstrated Fig. 3.3.5-1).
- A first attempt of using nitrogen pre-cooling showed not sufficient stability. With a new operation parameter set a stable operation was possible with TOSKA.

In general, the whole cryogenic system worked well. The operation of the TFMC configuration required some specific additions which will have no impact on the function of the basic system.

The cooling conditions and thermohydraulic properties after quench or dump are summarized in Table 3.3.5-1 and Table 3.3.5-2.

- Testing operation mode and unattended standby operation at nights and weekends were successfully demonstrated.
- Fault conditions during operation were successfully mastered without helium release to the atmosphere.
- A helium mass flow of 275 g/s was circulated over hours (Fig. 3.3.2.2-3).
- The operator crew were trained to handle the system.

Table 3.3.5-1 : Cooling conditions for the operation of the LCT coil during testing

Operation mode	**3.5 K**	**1.8 K**	**Standby at 1.8 K**
Winding			
Mass flow rate [g/s]	50	80	20
Pressure [bar]	3.5	2.4	3.5
Pressure drop [bar]	<0.1	0.6	0.07
Total heat load [W]	10	27	25
Case & structure			
Mass flow rate [g/s]	50	70	40
Pressure [bar]	3.5	3.4	3.5
Pressure drop [bar]	<0.1	<0.1	<0.1
Heat load [W]	100	90	90
Current leads			
Mass flow rate [g/s]	2 x 1.6	2 x 2.0	2 x 0.3
Heat load to winding [W]	2 x 5	2 x 8.5	2 x 12.5
Current per lead [kA]	16	19	0

Table 3.3.5-2: Thermohydraulic properties after dump and quench (peak values) of the LCT coil testing

Operation mode		**3.5 K** **16 kA** **Dump**	**1.8 K** **19 kA** **Dump**	**1.8 K** **19.6 kA** **Quench**
Winding				
Inlet temperature	[K]	14.6	11.7	26.5
Outlet temperature	[K]	8.8	11.0	17.4
Pressure	[bar]	5.3	8.8	26.6
Heat load	[MJ]	0.38	1.60	2.00
Case				
Inlet temperature	[K]	12.5	17.5	24.3
Outlet temperature	[K]	18.4	21.0	21.7
Pressure	[bar]	5.6	18.1	13.4
Heat load	[MJ]	1.10	1.30	1.65

The horizontal current lead installation of the LCT coil indicated losses which were twice as high as expected. This fact forced a design change for the installation of the 80 kA current leads which would exceed in horizontal installation position the capability of the cryogenic system (Fig. 3.3.5-1) (see section 3.3.4).

For the test of the W 7-X prototype coil, two new current leads were built with the improved design (hole diameter in the cooling fines reduced from 1.5 mm to 1 mm, meandering gas flow through the heat exchanger). 'The improvements were effective during testing. The losses were in the expected range. The operation showed no instabilities. Therefore this current leads will be installed for the LCT coil.

3.3.6 References

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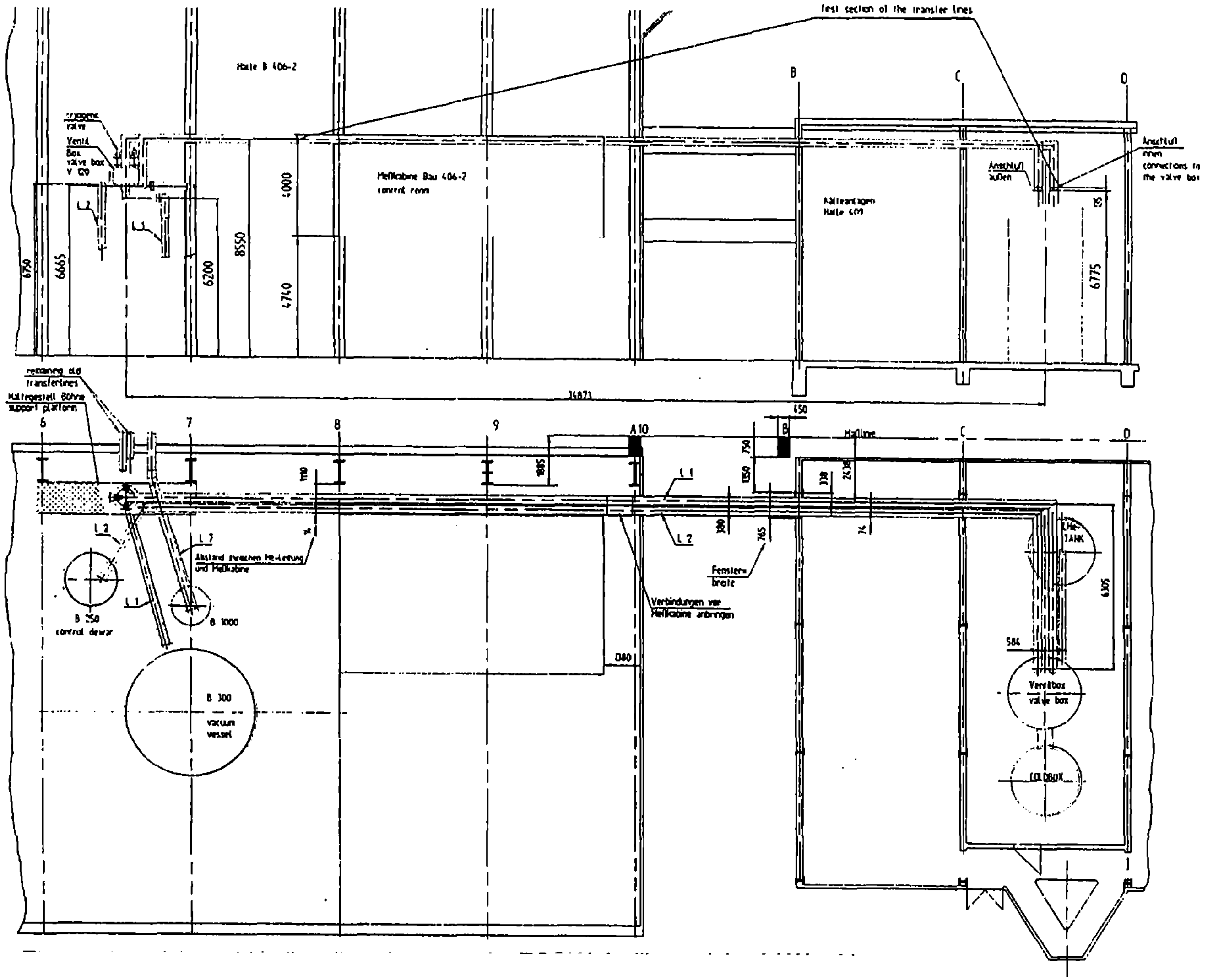

Fig. 3.3.1-1: The routing of the cold helium lines between the TOSKA facility and the 2 kW refrigerator

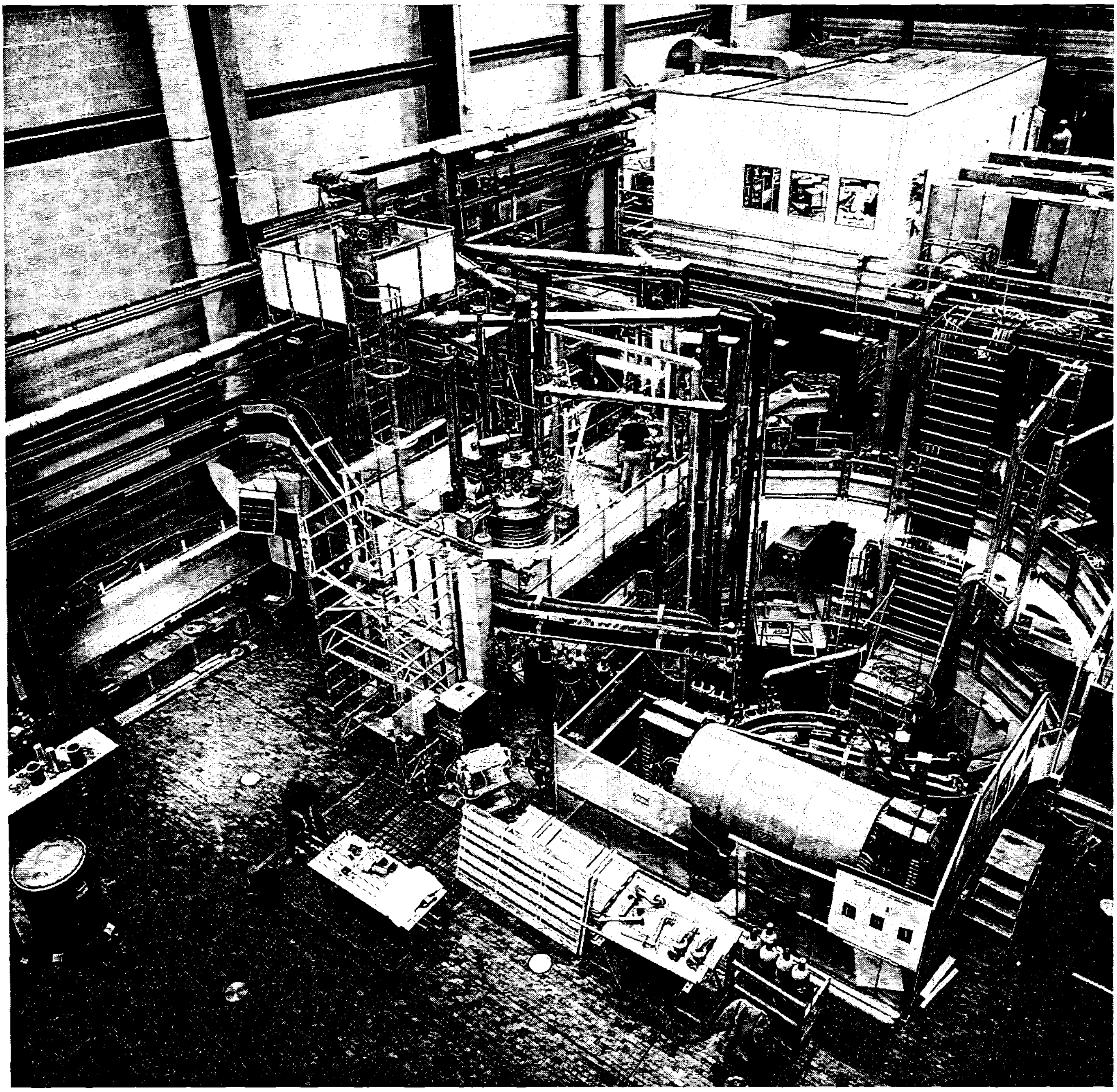

Fig. 3.3.1-2: The cold supply lines coming from the 2 kW refrigerator are in the upper right corner. One line terminates in the control cryostat B250 (containing the heat exchanger and pumps). The other line terminates in the valve box. The line is branched off in the valve box in two lines. One line runs to the B 300 (TOSKA vacuum vessel and is used for cooldown. The other line runs to the STAR facility. The reinforced LCT coil is seen in the left corner.

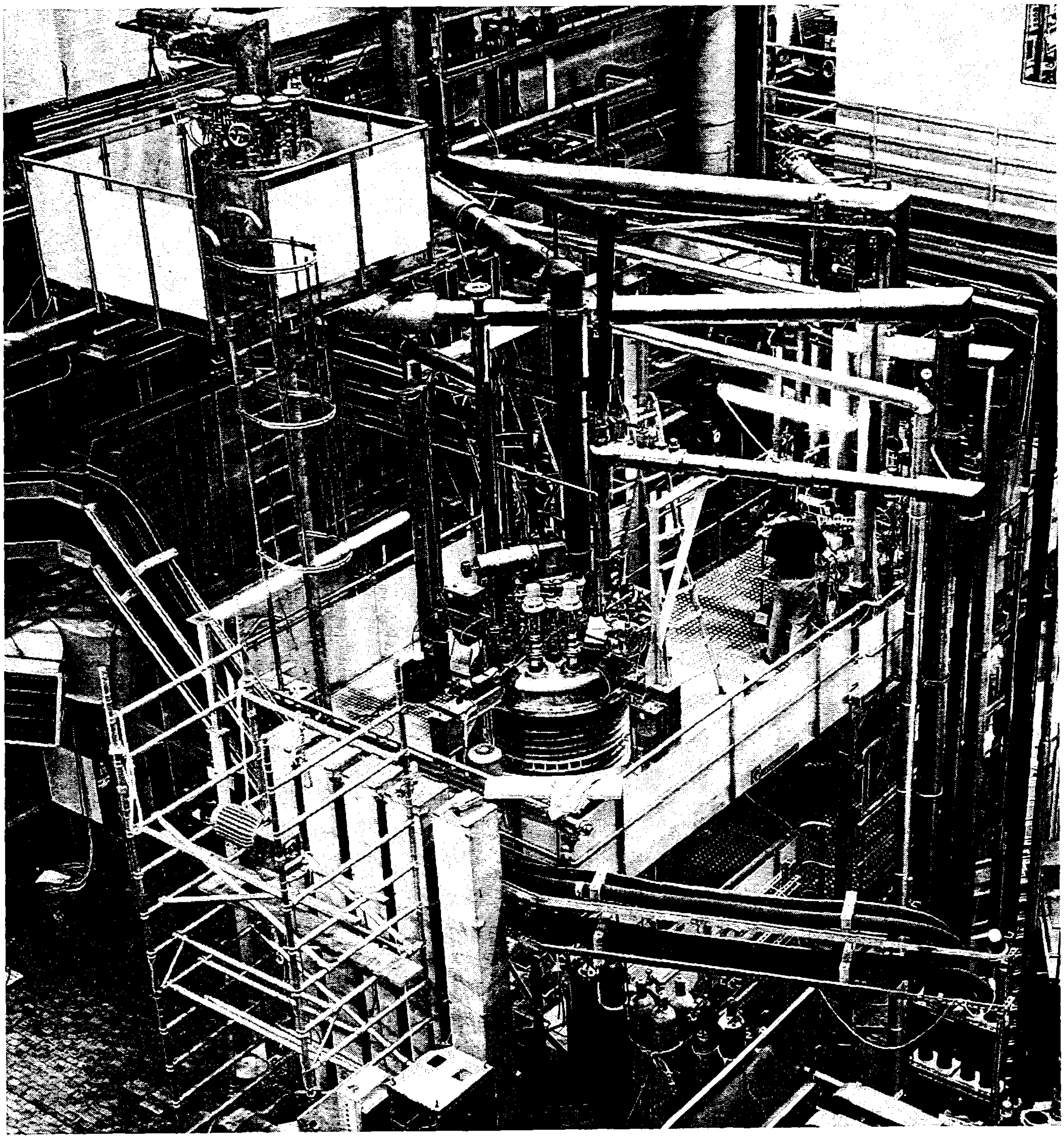

Fig. 3.3.1-3: Section blow up of Fig. 3.3.1-1 showing the core of the cryogenic supply system: The valve box, the control cryostat B250 (>3.5 K operation) and, on the right hand side, the control cryostat B1000 (>1.8 K operation).

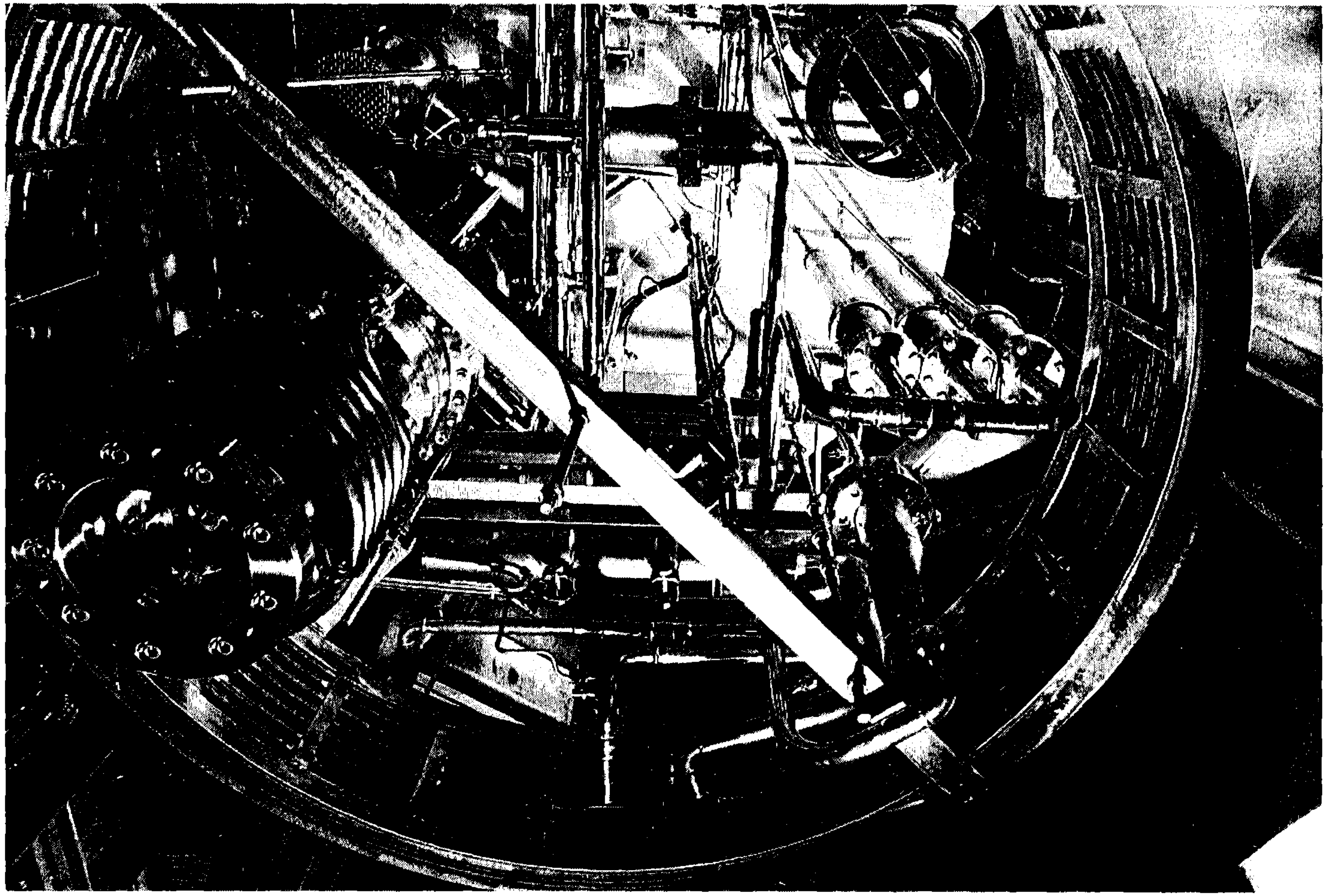

Fig. 3.3.1-4: A glance into the B1000 in direction from bottom to top: On the left hand side the thermomechanical pump, on the right hand side the 3 piston pumps and the centrifugal pump beneath surrounded by the heat exchanger

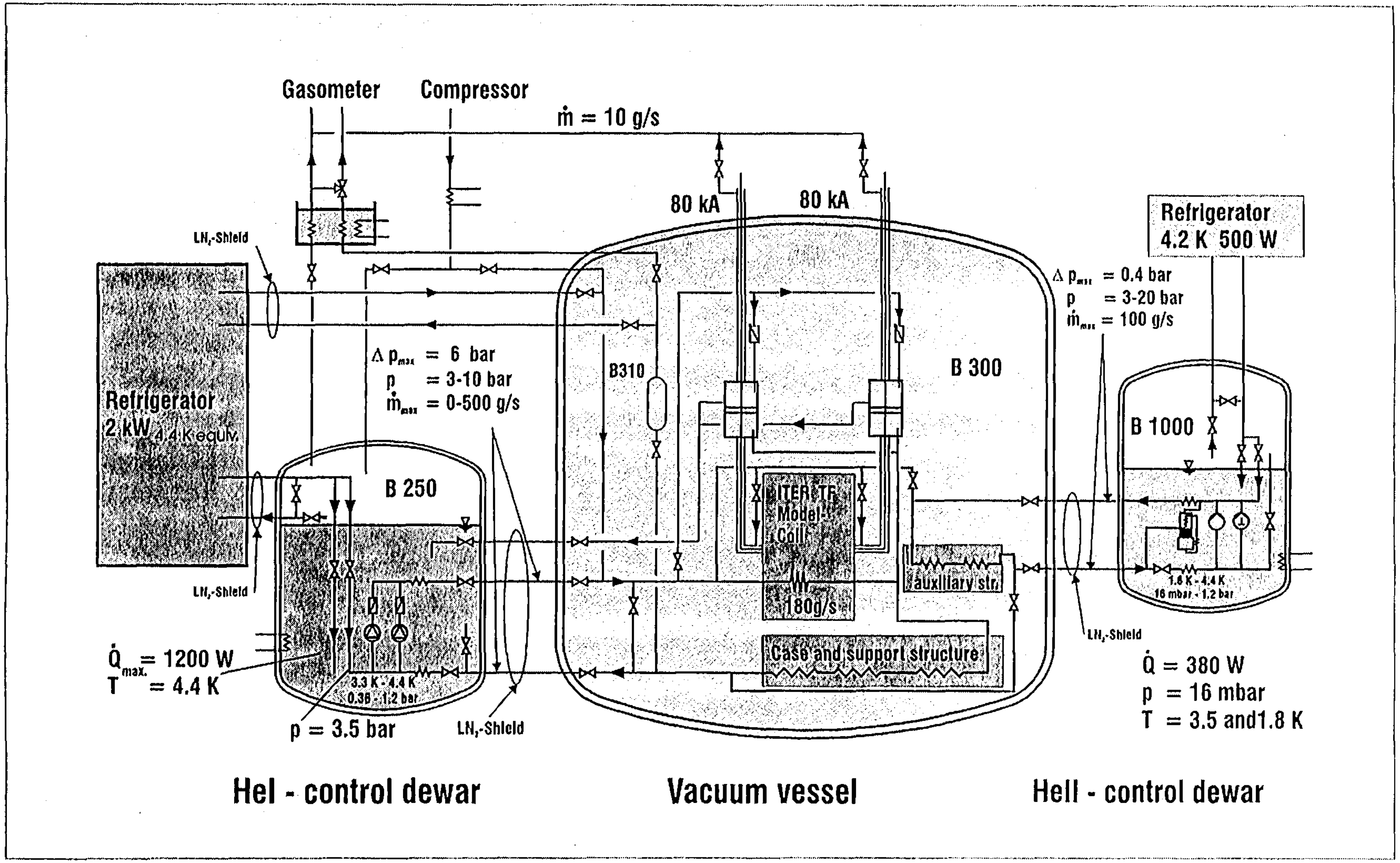

Fig. 3.3.2-1: The cooling scheme used for the TFMC testing without LCT coil

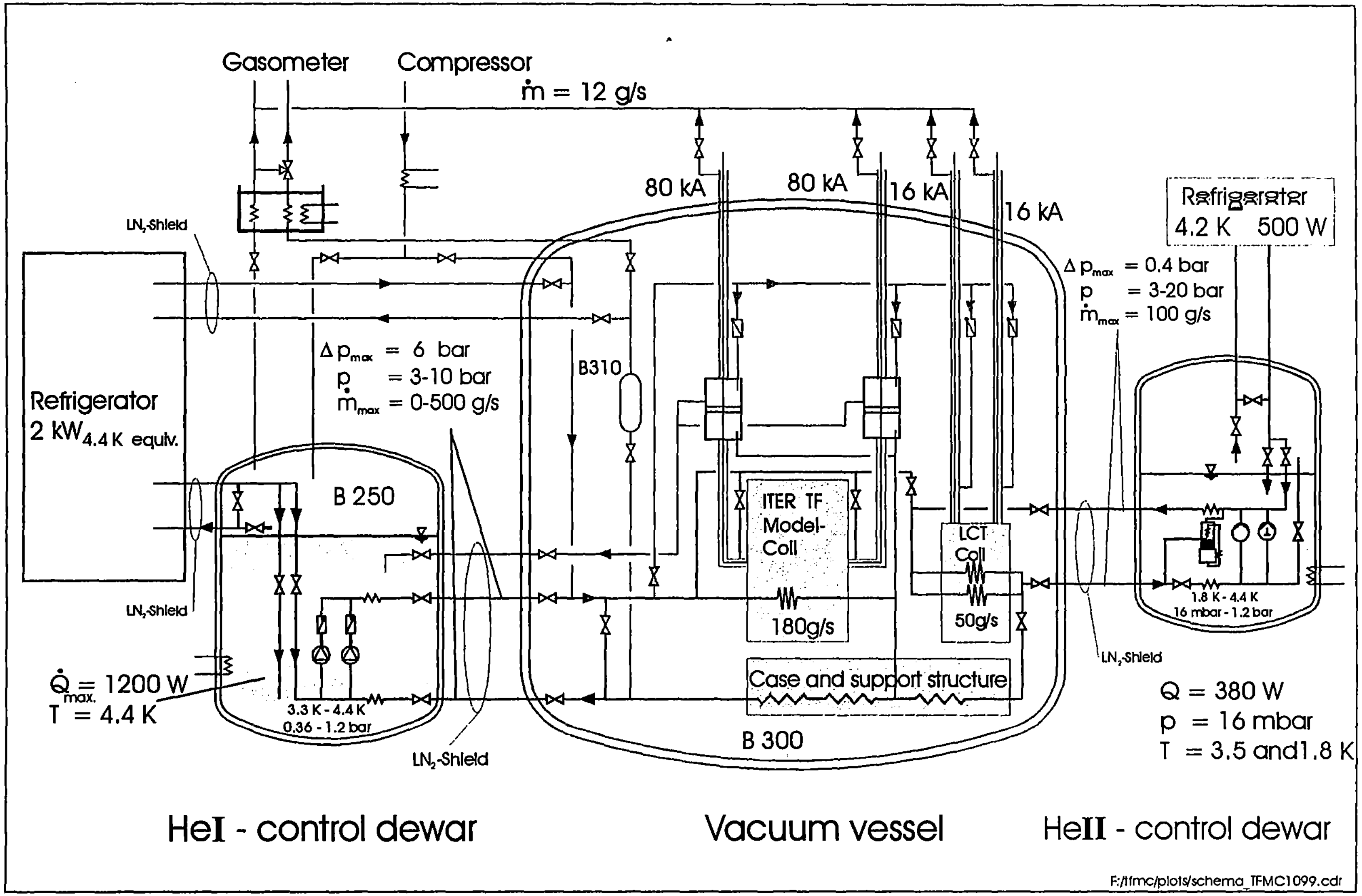

Fig. 3.3.2-2: The cooling scheme used for the TFMC testing with LCT coil

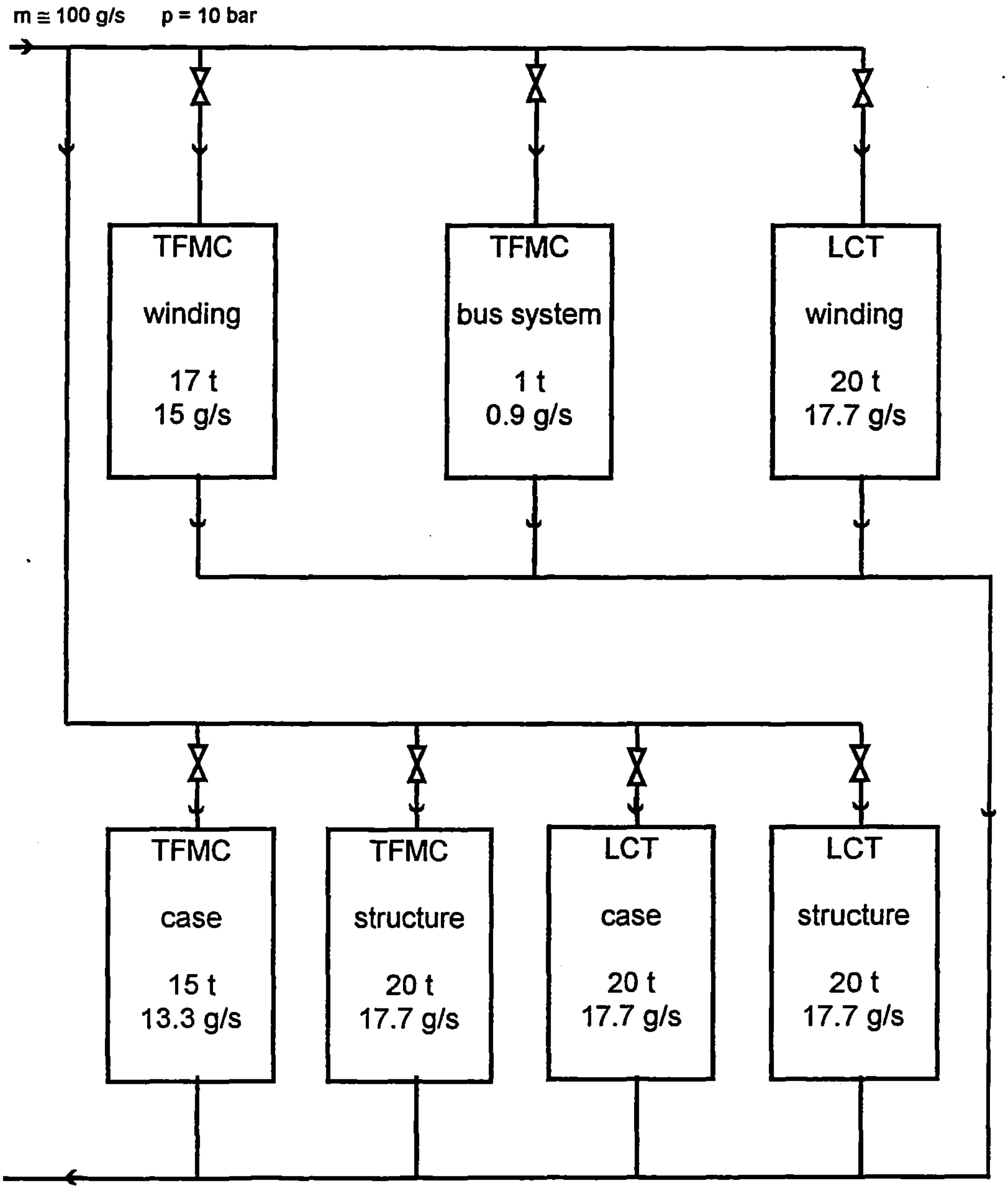

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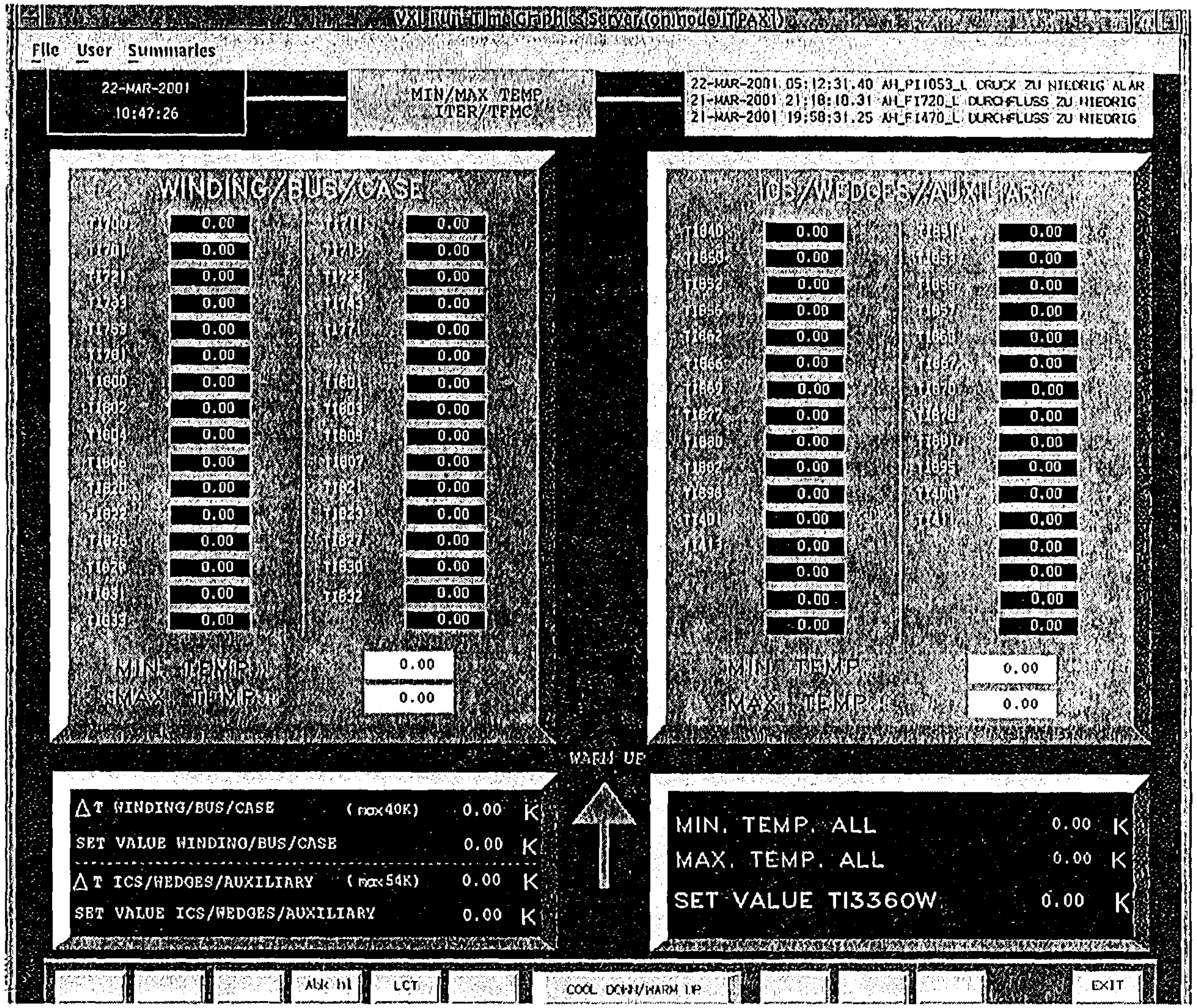
Fig. 3.3.2.1-1 : Mass flow distribution of the TFMC test configuration during cooldown. In the test without LCT coil LCT case or LCT structure is replaced by the auxiliary structure.



22-MAR-2001
10:47:26

```
22-MAR-2001 05:12:31.40 AH_PI1053_L DRUCK ZU NIEDRIG ALAR
21-MAR-2001 21:18:10.31 AH_FI720_L DURCHFLUSS ZU NIEDRIG
21-MAR-2001 19:58:31.25 AH_FI470_L DURCHFLUSS ZU NIEDRIG
```

```
ΔT WINDING/BUS/CASE        (max40K)   0.00 K
SET VALUE WINDING/BUS/CASE            0.00 K
-----------------------------------------------
ΔT ICS/WEDGES/AUXILIARY    (max54K)   0.00 K
SET VALUE ICS/WEDGES/AUXILIARY        0.00 K
```

```
MIN. TEMP. ALL          0.00 K
MAX. TEMP. ALL          0.00 K
SET VALUE TI3360W       0.00 K
```

Fig. 3.3.2.1-2: The control panel for the cooldown and the setting of the parameters as used for the TFMC test.

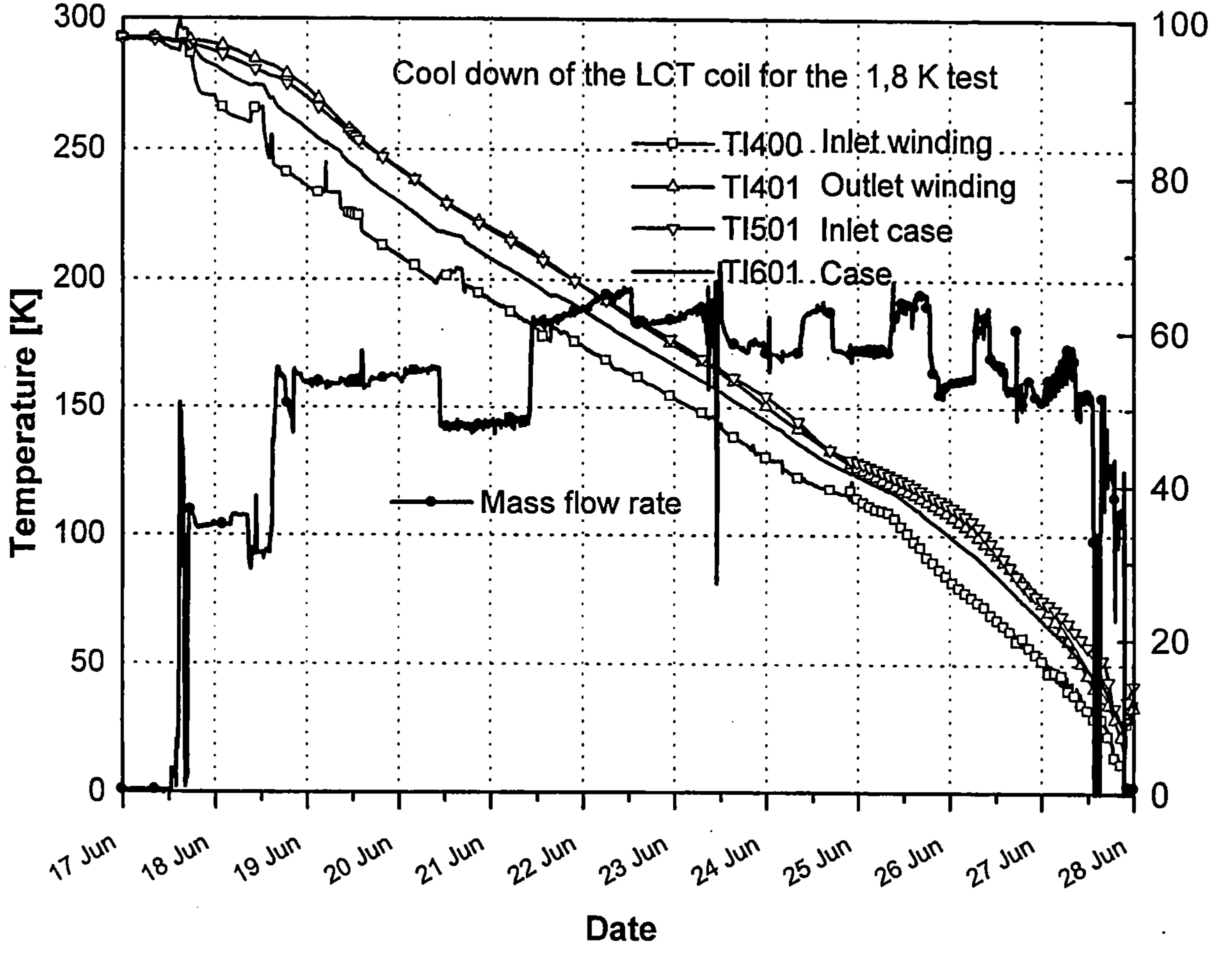


Fig. 3.3.2.1-3: The inlet and outlet temperatures for winding and coil case as well as the total mass flow rate during cooldown of the LCT coil for the 1.8 K test

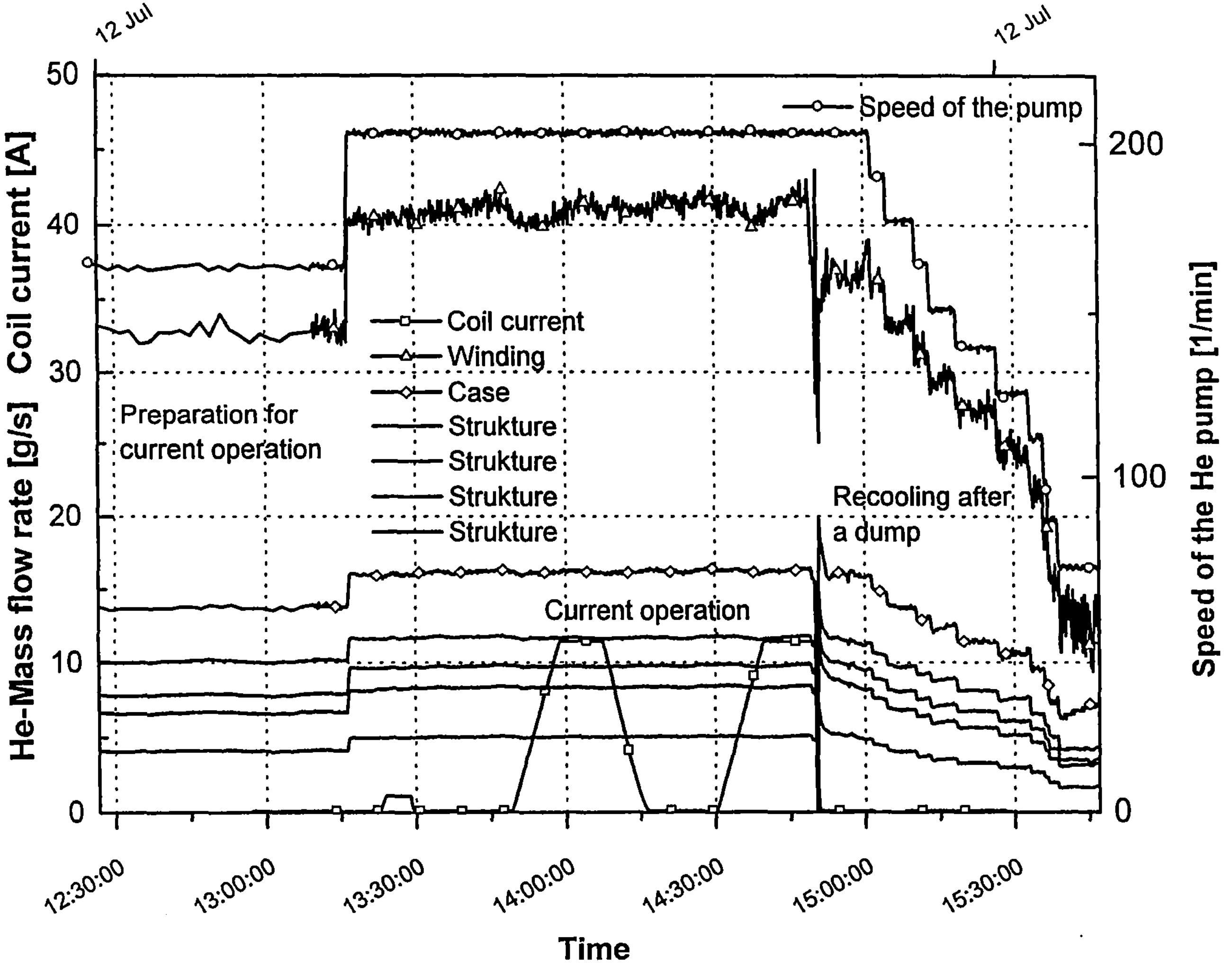


Fig. 3.3.2.2-1: Mass flow distribution during current operation with ramping and dumping

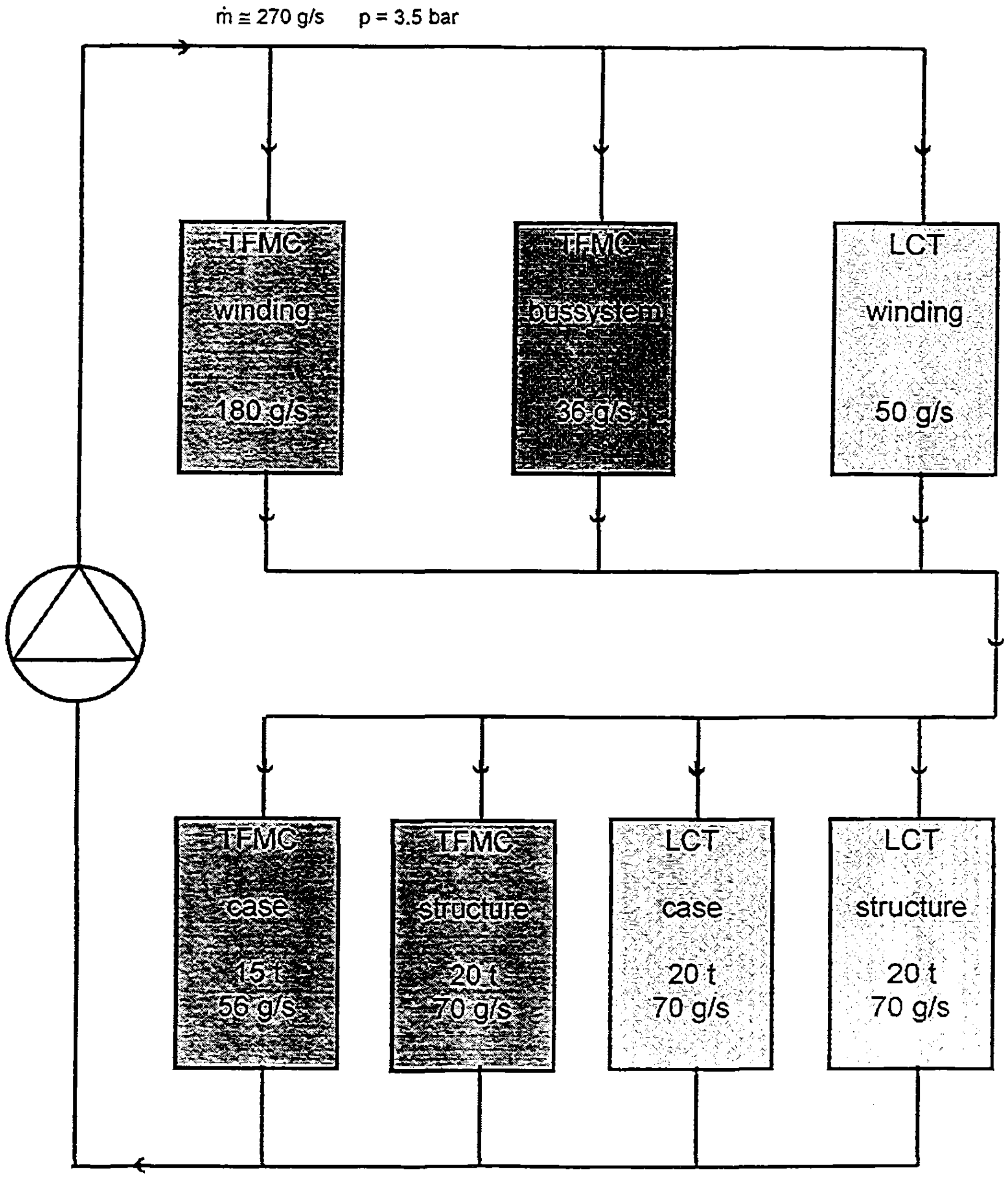


Fig. 3.3.2.2-2: Proposed mass flow distribution for operation of the TFMC configuration

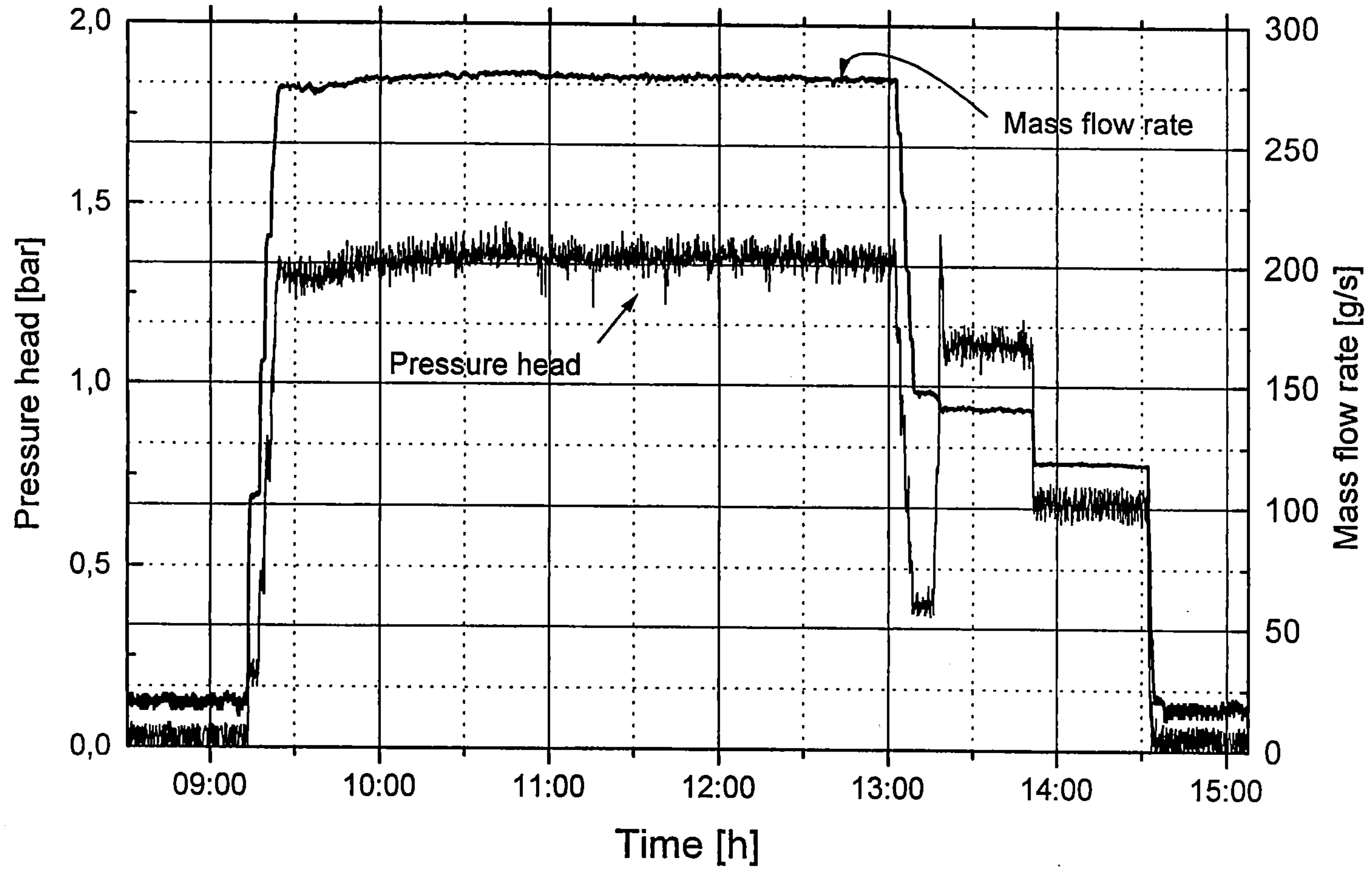


Fig. 3.3.2.2-3: Combined operation of two piston pumps in parallel generating 275 g/s mass flow

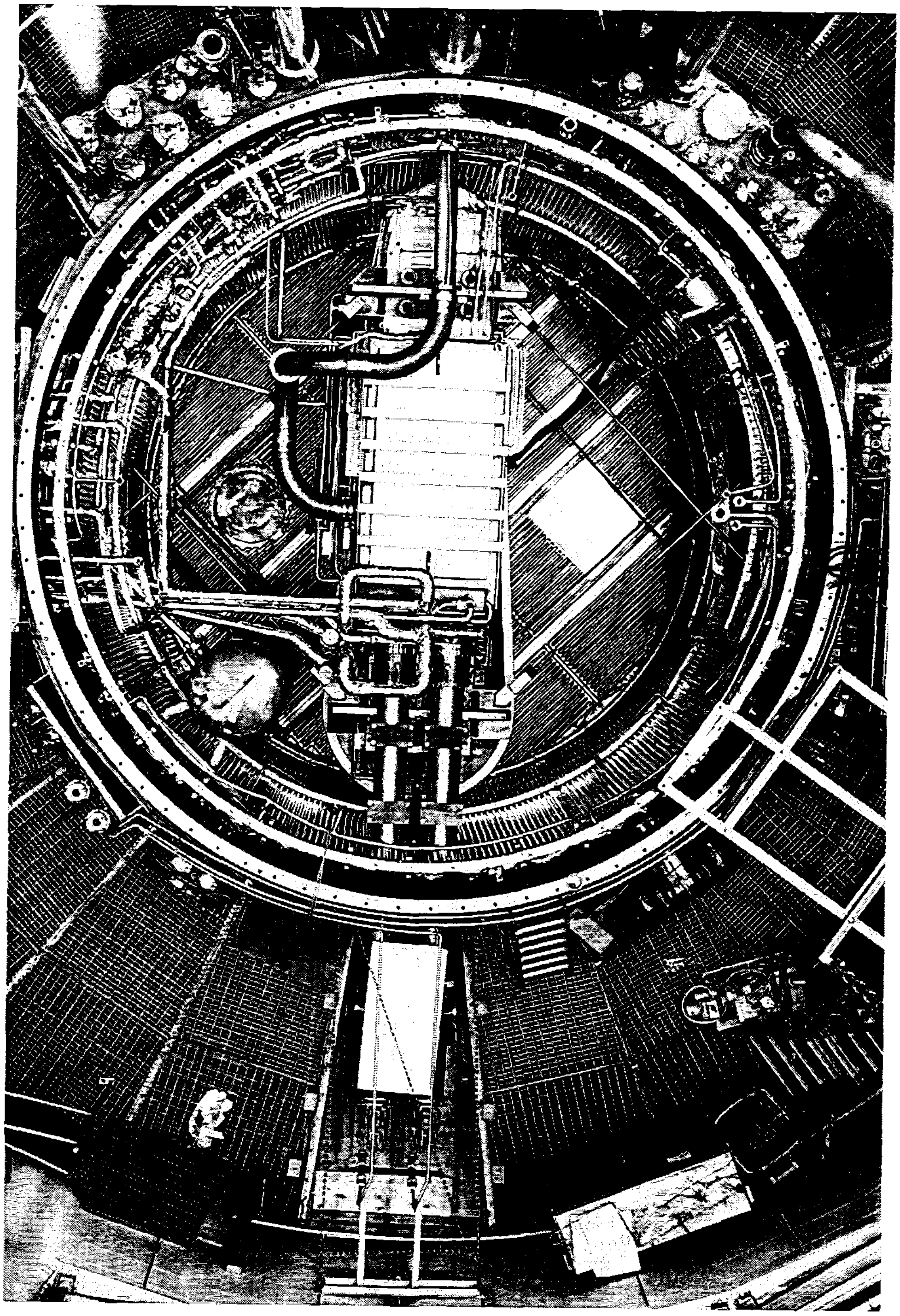


Fig. 3.3.3-1: The reinforced LCT coil installed in the TOSKA vacuum vessel in the same position like for the TFMC test. The space for the TFMC + ICS is on the right hand side. In the left hand corner, the cold quench storage pressure vessel is visible. The two ports for the TFMC current leads are on the right hand side.

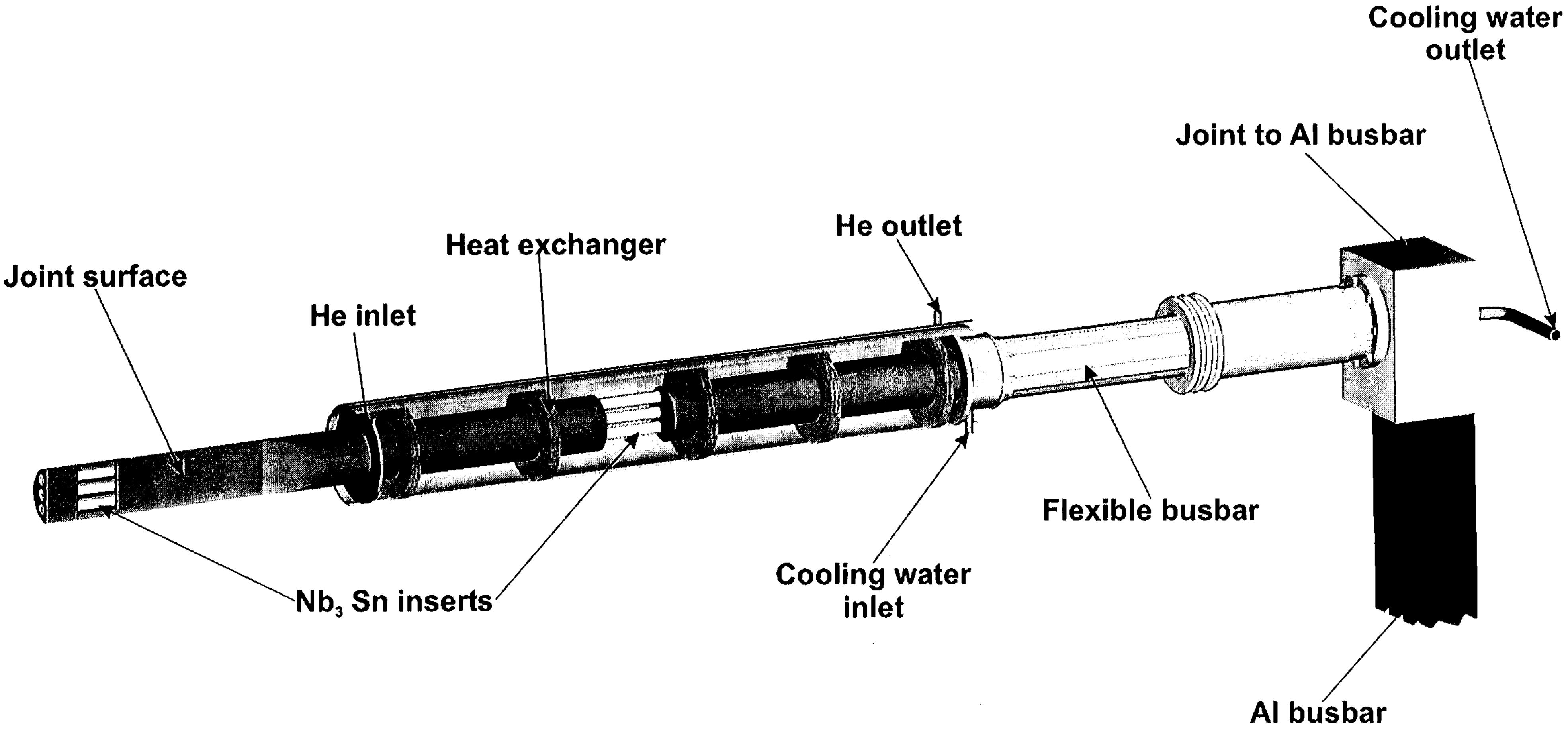


Fig. 3.3.4-1: Artists view of the 80 kA current lead characterized by a cold end with 3 Nb_3Sn inserts and a water cooled busbar

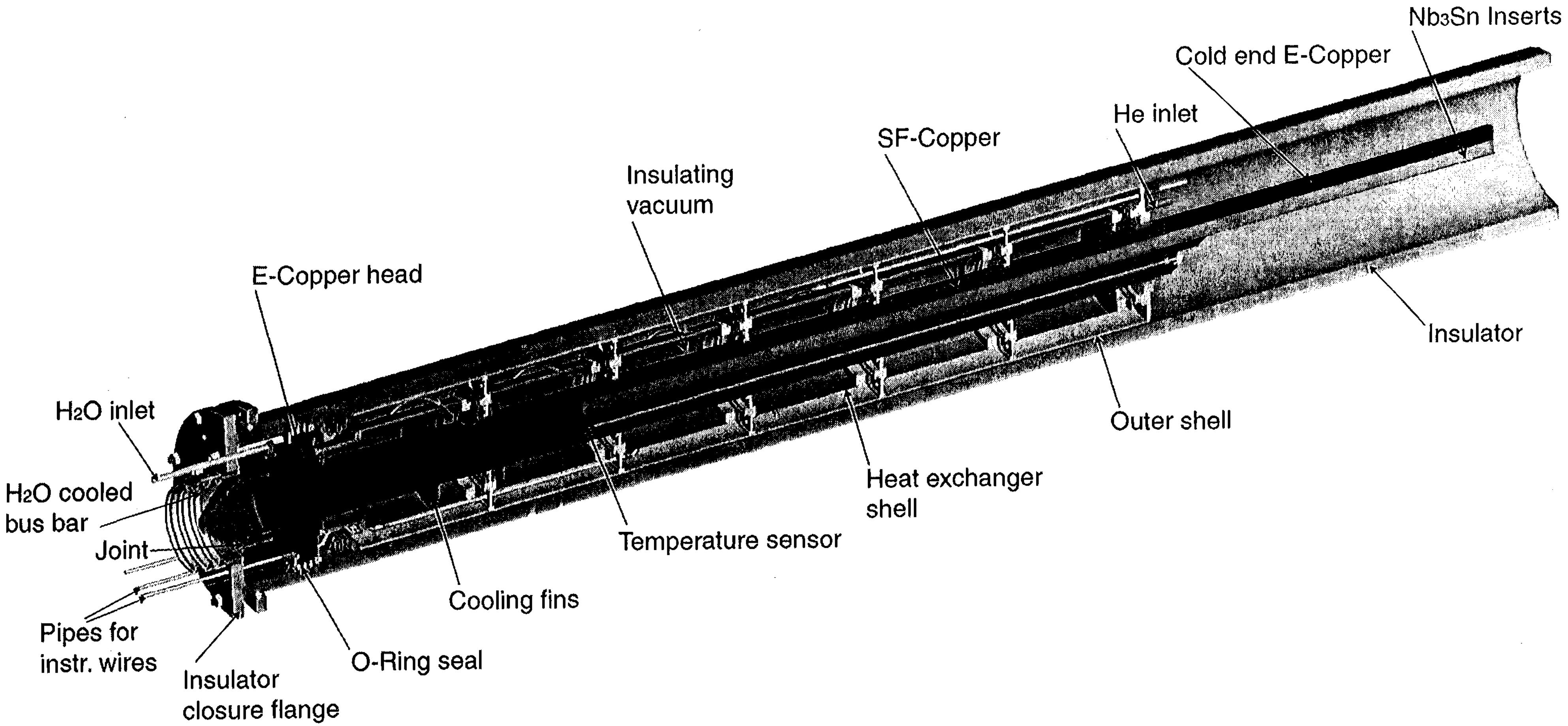


Fig. 3.3.4-2: The final detailed design of the 80 kA current lead

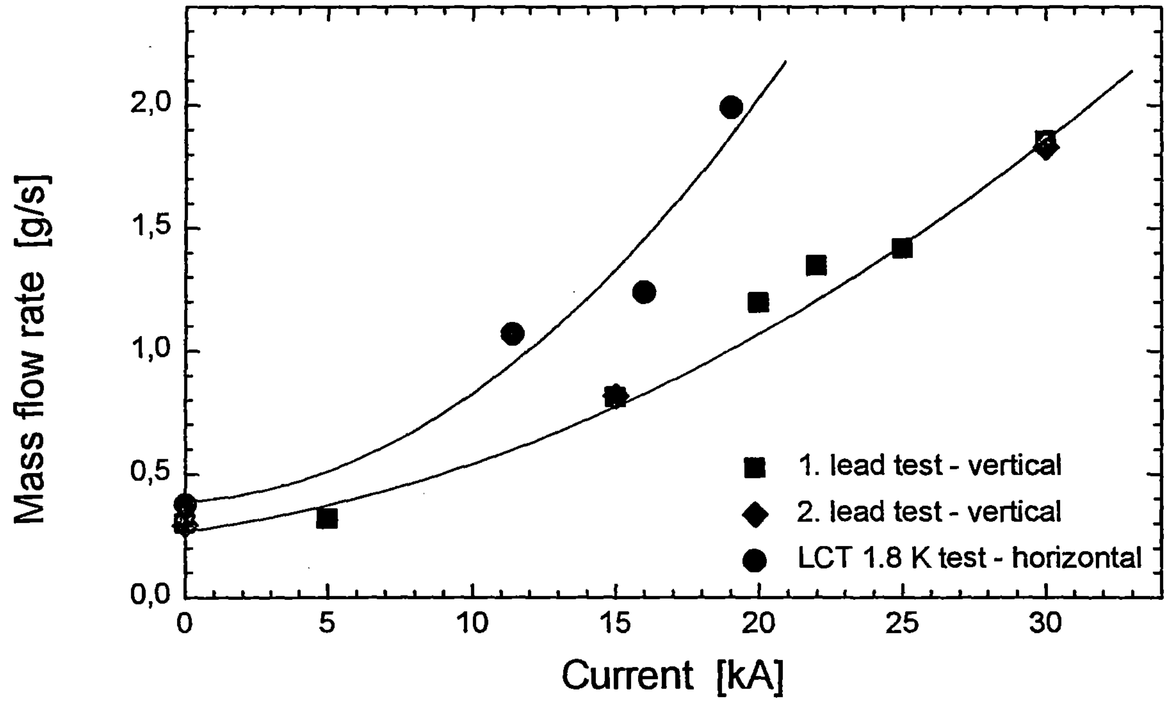


Fig. 3.3.4-3: Comparison of mass flow rates of the 30 kA current leads for vertical (POLO) and horizontal (LCT, 1.8 K test) installation

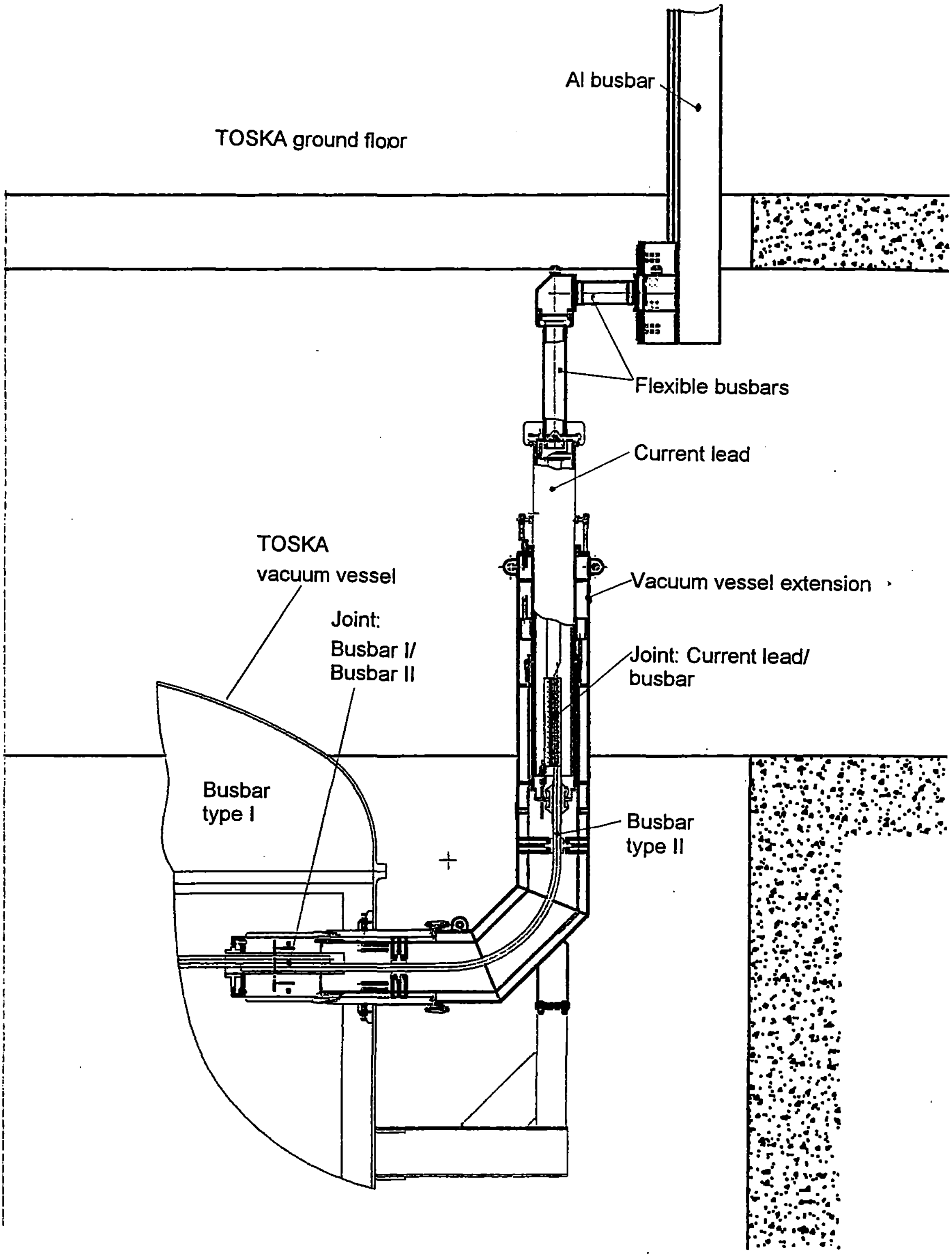


Fig. 3.3.4-4: The vertical installation of the 80 kA current leads in the TOSKA vacuum vessel

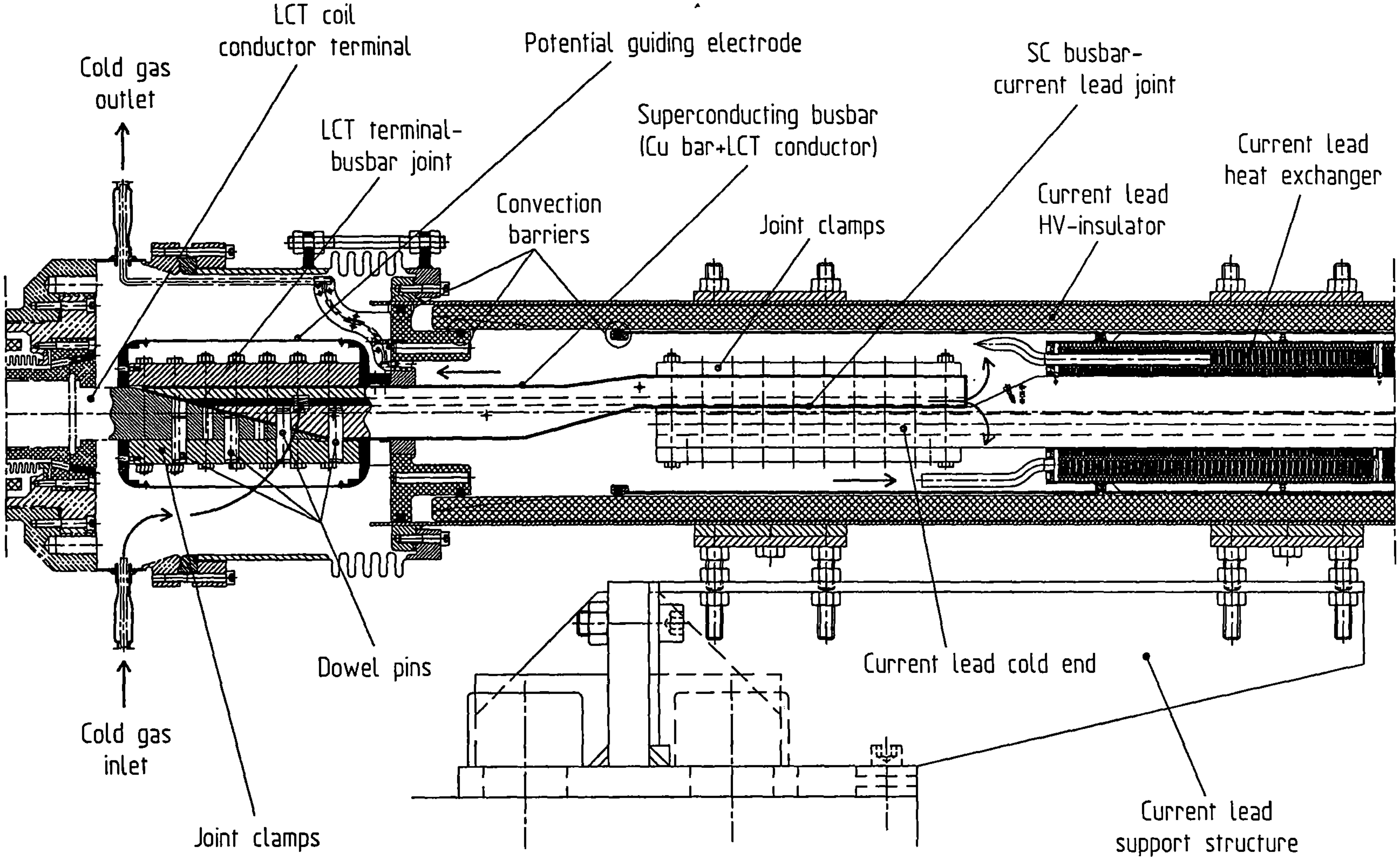


Fig. 3.3.4.1-1: The cross-section of the joint technique between current lead and LCT coil conductor terminal by a superconducting busbar

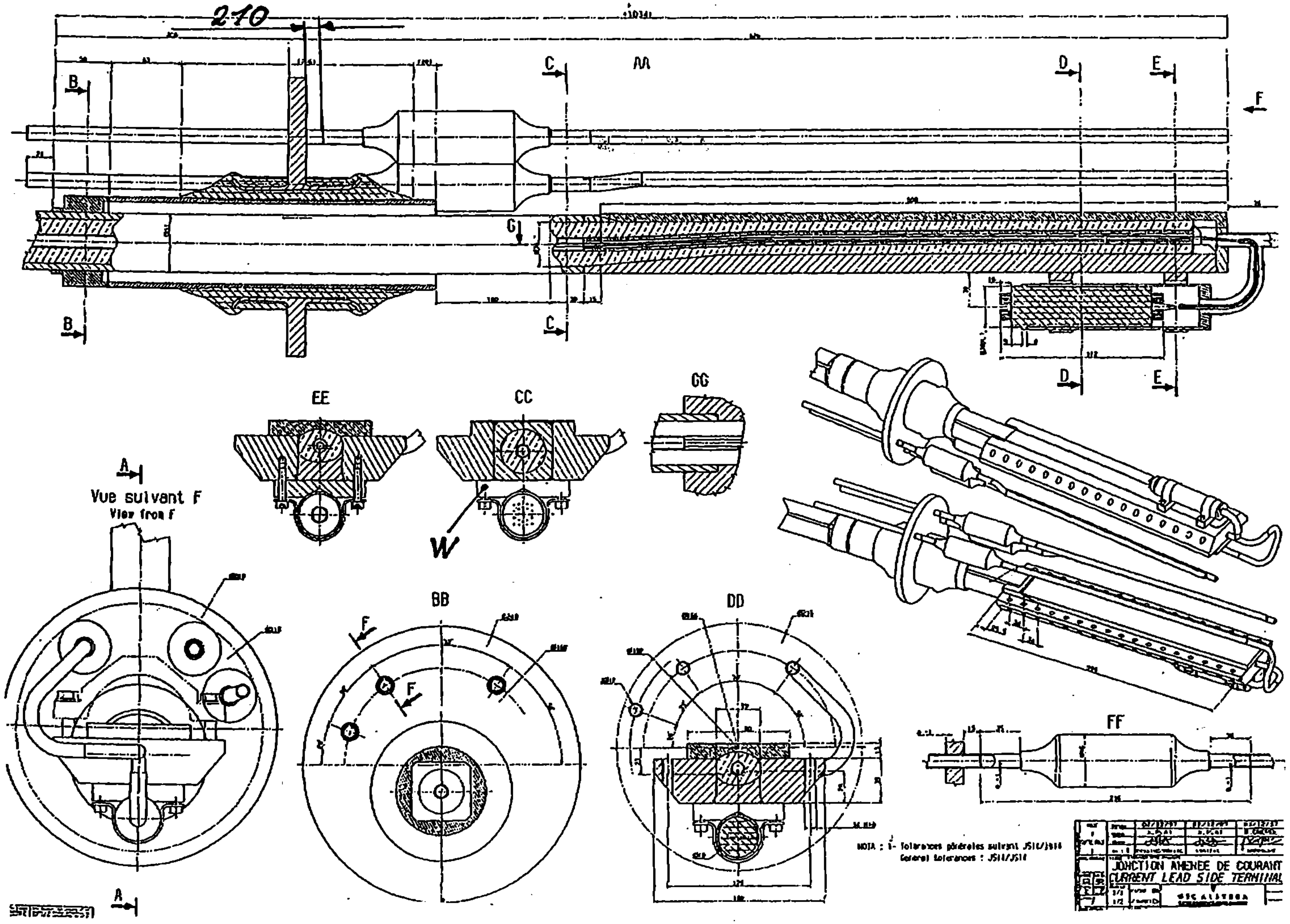


Fig. 3.3.4.1-2: The design of conductor terminal of the TFMC Type II superconducting busbar by Alstom, Belfort as presented in Fig. 3.3.4.1-3

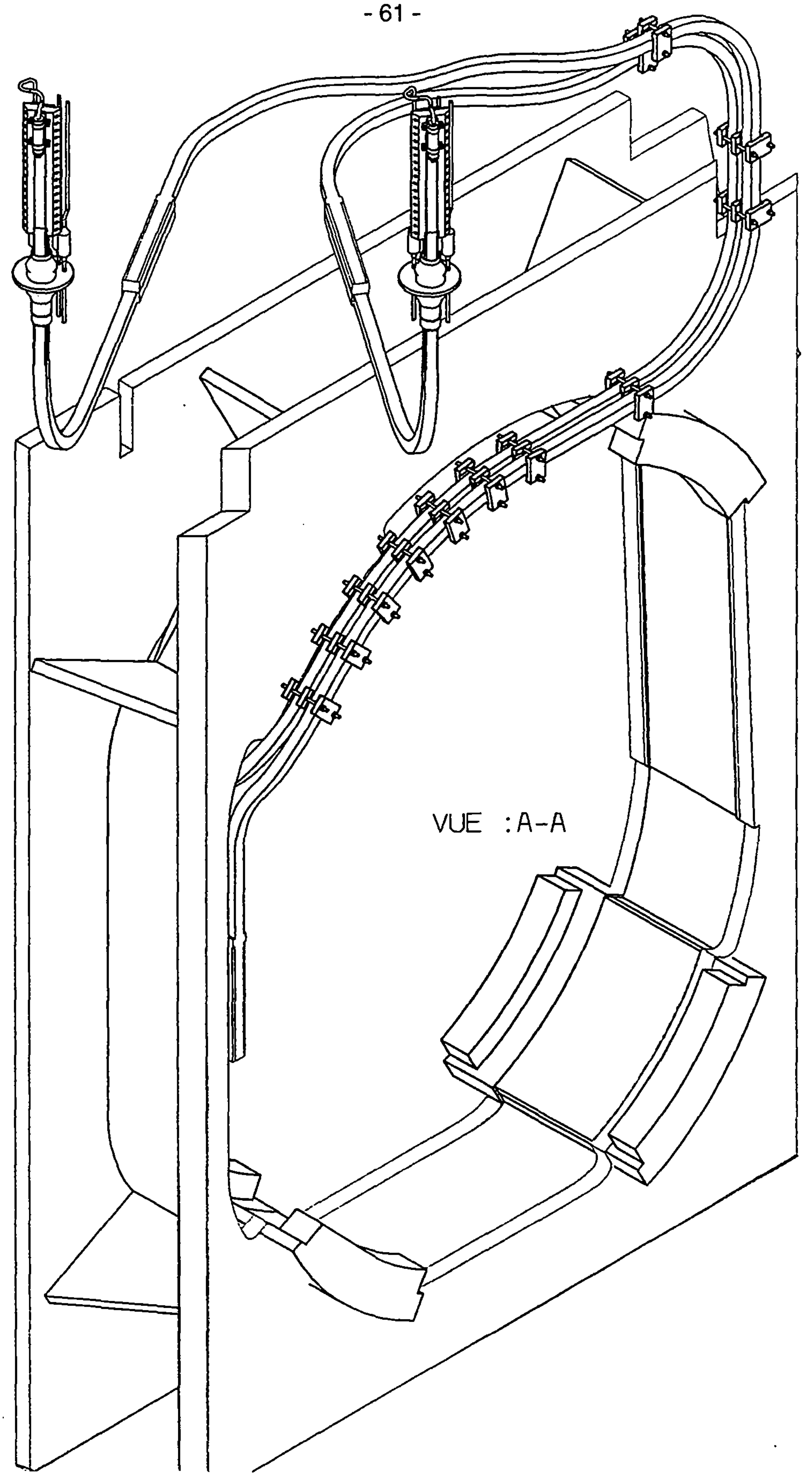


Fig. 3.3.4.1-3: Design of the routing of the superconducting busbars in the TOSKA vacuum vessel according to a drawing of Alstom, Belfort

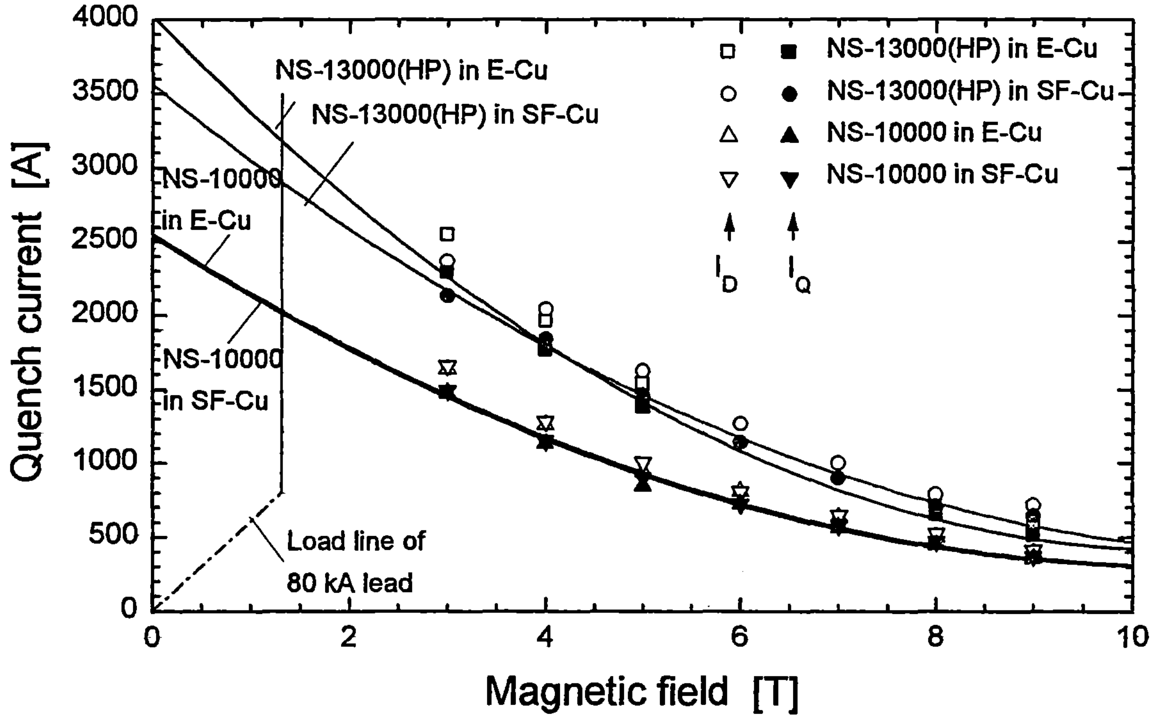


Fig. 3.3.4.3-1: Quench current vs. magnetic field for Vacryflux NS-13000HP and NS-10000 strands embedded in electrolytic copper respectively phosphorous deoxidized copper

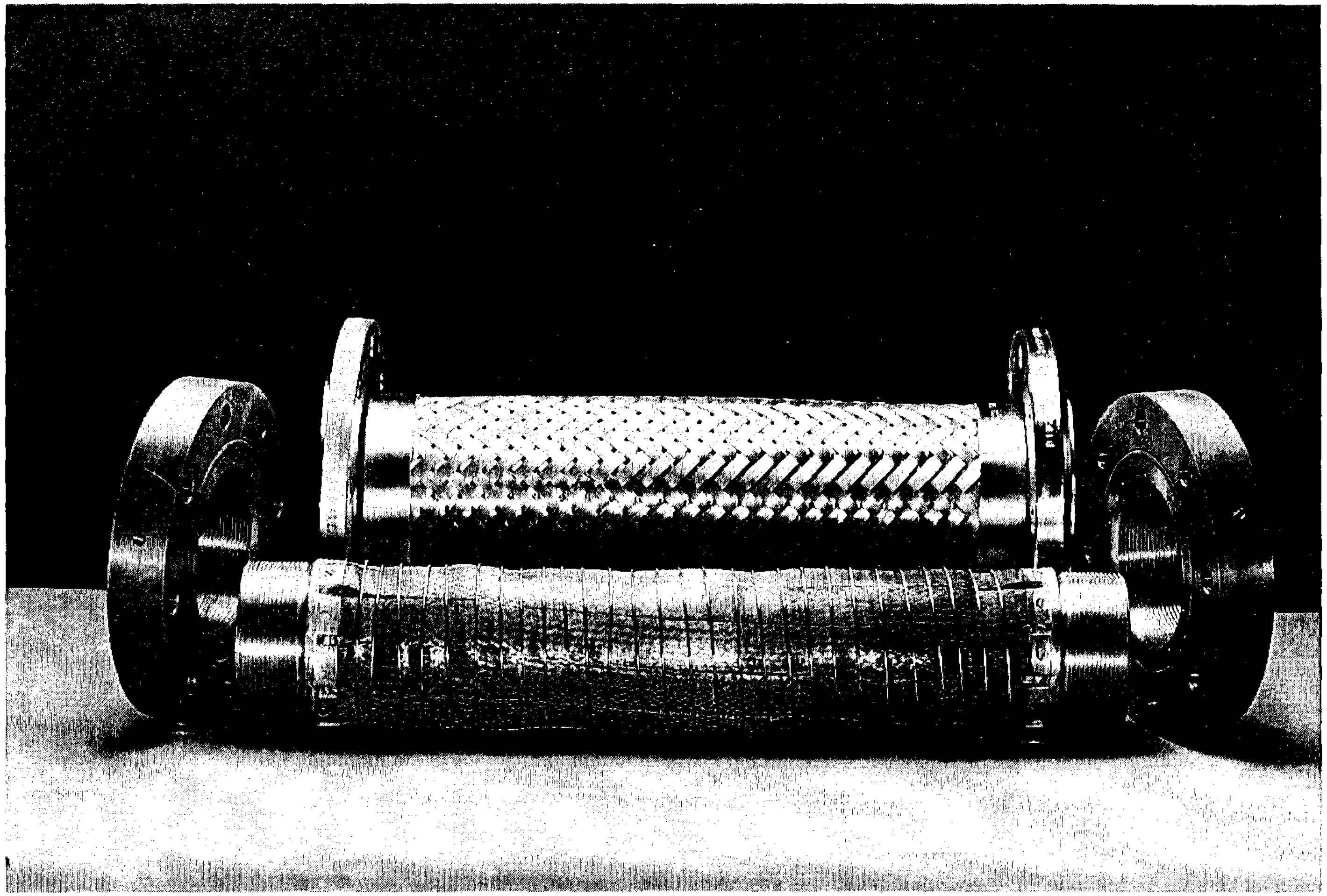


Fig. 3.3.4.4-1 : Busbar made from copper braids which are mounted in a corrugated tube

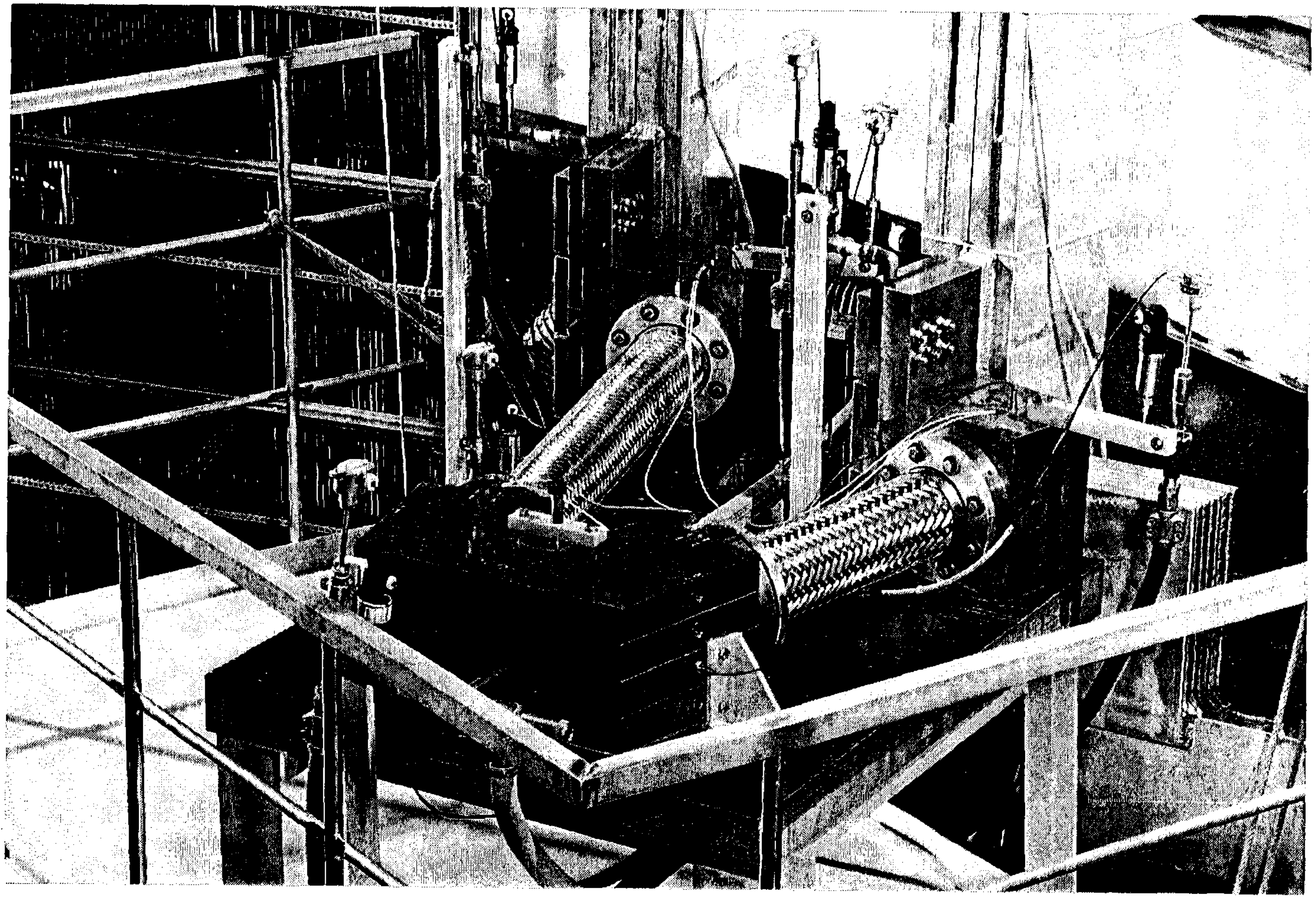


Fig. 3.3.4.4-2: Experimental arrangement of testing the developed busbar system short circuited by a solid copper busbar

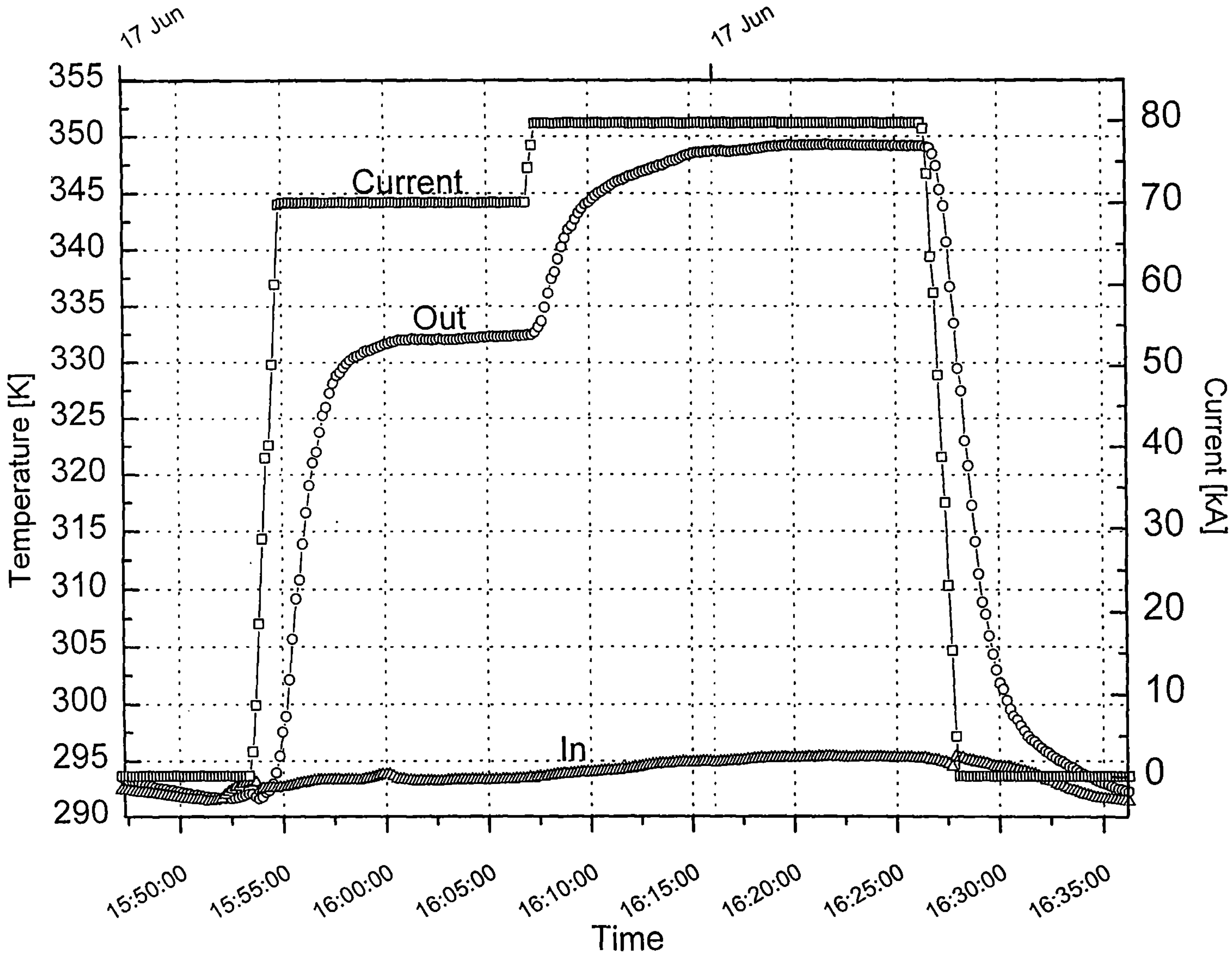


Fig. 3.3.4.4-3: Inlet and outlet temperature profiles as well as the current during the test of the busbar.

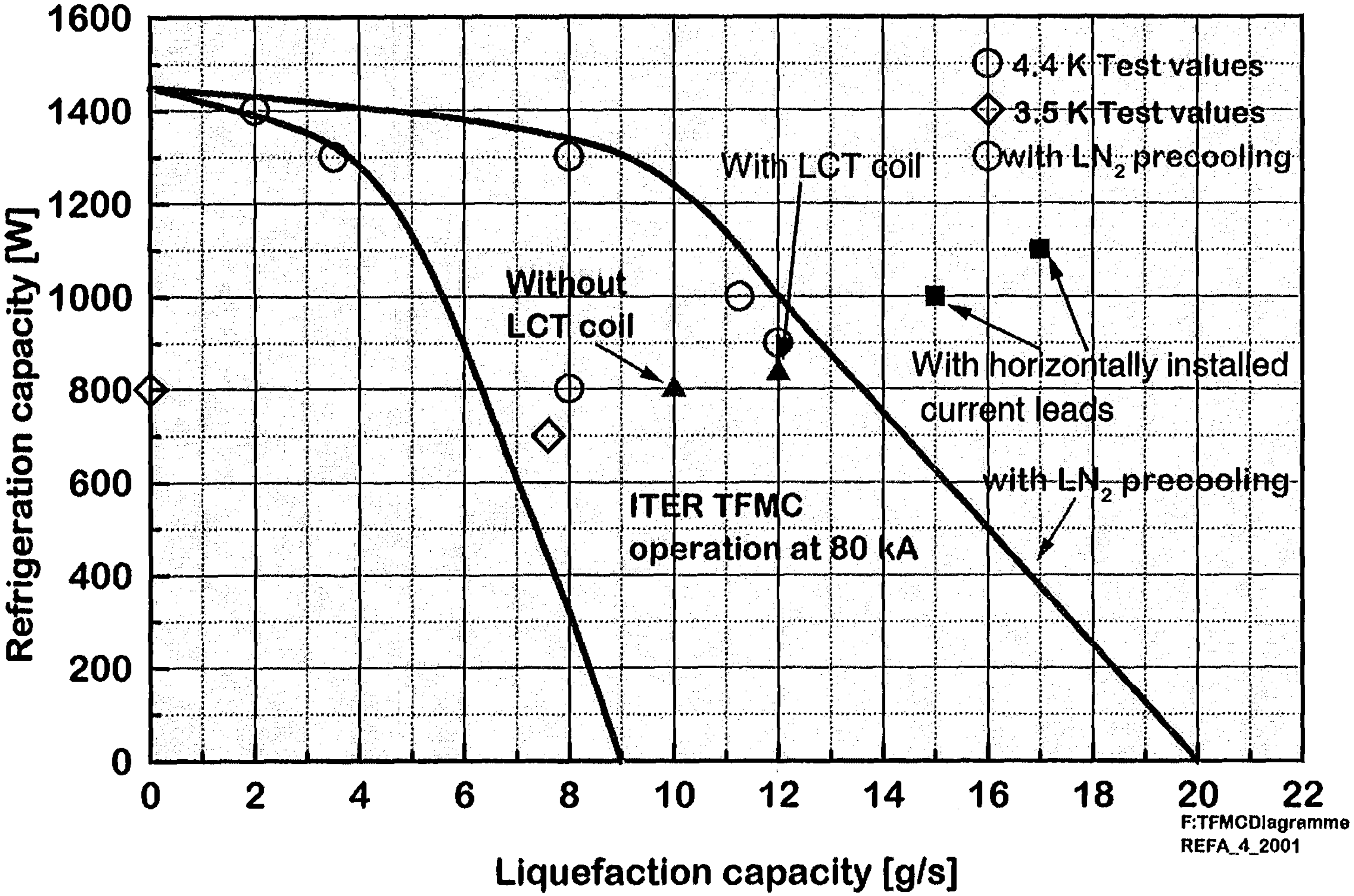


Fig. 3.3.5-1: Measured refrigeration and liquefaction capacity at the control cryostat B250 and the rated operation point for testing TFMC without and with LCT coil. The operation points for horizontal installed current leads are outside the capability of the cryogenic system (lower value 70 kA, higher value 80 kA).

3.4 Current supplies and dump circuits

3.4.1 General description, overview

The TOSKA facility has for the 80 kA operation two 12 pulse thyristorized DC power supplies with an output voltage of ± 30 V. One of them has a maximum current of ± 30 kA, the other one of + 50 kA. These power supplies are equipped with a busbar system and a control unit so that the power supplies can be operated as single power supplies or both switched in parallel so that a total current of 80 kA can be achieved (Fig. 3.4.1-1 to 3).

A new 12 pulse thyristorized DC power supply with an output voltage of ± 30 V and a maximum rated current of 20 kA is installed and taken into operation for the LCT coil for the test configuration LCT+TFMC.

An important circuit in the high current network of a superconducting magnet is the dump circuit for the removal of the stored energy in case of a quench. General in case of the discharge of an inductance L in a resistor R the relation between discharge voltage U, current I, time constant τ ($\tau = L/R$)and stored energy E, is defined by the relation

$$E = U \cdot I \cdot (\tau/2)$$

In Table 3.4.1-1 typical discharge parameters are summarized for magnets tested or magnets that will be tested in TOSKA in near future.

Table 3.4.1-1: Discharge parameters of tested magnets as single coil (upper part of the table) and magnets that will be tested in next future in the TOSKA facility (middle part of the table). The lower part of the table gives the discharge parameter for discharge segments of the ITER (20) and W 7-X (7) torus (Number of discharge segments in brackets).

Coil	**Discharge type**	**E [MJ]**	**I_o [kA]**	**U_o [kV]**	**P_o [MW]**	**τ [s]**
POLO	Safety	4.81	24	0.72	17.2	0.56
"	High voltage	1.87	15	22.0	330.0	0.011
LCT	Safety	302.0	19.6	2.45	48.0	12.5
W 7-X prototype coil	Safety	8.0	16	0.53	8.5	1.9
ITER TF model coil	Safety	86.2	80	0.539	43.0	4.0
	High voltage	8.0	24.3	10.0	24.3	0.066
ITER TF coils torus Segment	Safety	~ 500.0	60	10.0	600.0	15.0
W 7-X coil torus segment	Safety	~ 86.0	20.0	8.0	160.0	3.0

The table shows that voltage, current and also energy (W 7–X) of torus segments will be already achieved in TOSKA as single parameters

Besides the pure protection function of the discharge circuit, the circuit is also an experimental tool for generating defined test conditions. This was the case for the POLO dump circuit. Transient loading regarding high voltage and magnetic field were generated by special switching sequences.

The basic switching circuit used for the ITER TF model coil is presented in Fig. 3.4.1-4. The power supplies are connected across separation switches (ST) with the positive and negative bus bar running to the current lead terminals of the coil. The discharge resistor (R) is connected to the bus bars parallel to the coil (L). A short circuit branch parallel to coil and discharge resistor consists of two parallel working arc chute switches (S1, S2), in series with a third one (S3). This arrangement assures that a fault operation of one switch during closing or opening procedure leads to no failure of the safety discharge. So far, the dump circuit has a simple redundancy.

A programmable logic controller (PLC) controls the switching circuit. The switching sequence of the safety discharge is redundantly assured by a parallel running relay circuit. In case of triggering a dump, the arc chute switches are closed. The power supply is switched in inverter mode (negative output voltage). The power supply feeds back the stored energy of the circuit to the grid and commutates the current on the branch (S1, S2, S3). The coil is now shorted across this branch. The separation switches (ST) open and isolate the power supply from the dump circuit. Then, the arc chute switches (S1, S2, S3) open simultaneously. The increasing arc resistance commutate the current into the discharge resistor. The coil current decreases exponentially with the time constant τ.

The power supply is protected by an overvoltage protection (OV). In case of an unexpected power outage from the grid side, the last two fired thyristors carry the portion of the DC current in each power supply in the freewheeling mode. A safety discharge is immediately initiated. The full coil current is then branched according to the short circuit resistance in the branch (S1, S2, S3) and the differential thyristor resistance of the two power supplies in parallel. The branch current of the two power supplies is finally commutated by the separation switches ST in the short circuit branch (S1, S2, S3). At maximum current the commutation of the freewheeling current of the 30 kA power supply in the short circuit path (S1, S2, S3) is performed by the melting of the thyristor fuses. For the thyristor fuses of the 50 kA power supply, the load limit integral is always adequate large so that the switches ST commutate the current in the short circuit path (S1, S2, S3) [3.4.1-1].

In the case of an internal power supply fault the usual safety discharge is triggered and the AC high voltage power breakers open first when the inverter mode operation is concluded and the current is commutated on the short circuit path (S1, S2, S3).

In case of a quench (coils, sc bus bars) or faults the PLC of the dump circuit corresponds with the PLC of the cryogenic system and vice versa. In the first case for the beginning of the safety discharge, certain valves have to be set in order to avoid not acceptable pressure increases and helium losses. In the second case, fault conditions in the cryogenic supply system or somewhere else have to initiate a safety discharge.

3.4.2 20 kA dump circuit for the LCT coil

The basic circuit is given already in Fig. 3.4.1-1. The short circuit path needs a modification. The arc chute switches (Type AEG, GERAPID 6003) (3.1, 3.2) were capable to interrupt currents up to 80 kA. A special automatic trigger circuit is installed to open the switch if a certain short circuit current is achieved (about 12 and 16 kA) (Fig. 3.4.2-1). This can lead to problems at the separation switches (2.1, 2.2) when the current is not fully commutated to the short circuit path and the opening of 3.1 and 3.2 starts already the current commutation in the resistor 6.2. For avoiding the uncontrolled opening, two switches work in parallel so that the branch current is always < 12 kA. The closing function of the short circuit path is performed by two usual AC breakers (13.1, 13.2) in parallel operation so that the current can distribute itself equally on breakers 3.1 and 3.2. A malfunction of the breakers 3.1 and 3.2 can be compensated by an explosive driven separator switch (4.1) which commutates the current in two fuses (4.2). The fuses commutate the current then in the resistor (6.2). The separator switch and the fuses have to be replaced after such a current commutation. All branches are equipped with current transformers (Type LEM). Voltage transformers measure the voltage across the high current busbars, respectively the coil. This instrumentation is needed for the diagnostics of the safety discharge and the proper running down of the switching sequence.

The circuit is soft grounded. About 6 % of the current runs across the grounding resistor if a ground fault occurs at the not grounded coil side. The grounding can be disconnected in the operation mode "high voltage test" which will be performed each time before starting the daily experimental work.

For the test of the TFMC + LCT coil, the dump parameters are summarized in Table 3.4.3-1.

The task of the switches 10.1 and 10.2 are needed for disconnecting the dump resistor for tests and trouble shooting. They are controlled in such a way that they close before the current commutation in the dump resistor starts. During operation of the LCT coil, these switches were short circuited by a busbar. But for fast pulsing, they can remain open to reduce the losses in the dump resistor. It was an experience of the LCT coil test that for large inductances like for the LCT (1.58 mH) the switches (10.1,10.2) have to be closed otherwise the controller is not able to ramp up the current.

The 20 kA dump circuit can be operated with 50 kA power supply (ABB) or with the 20 kA power supply (Bruker). There is a switch panel in the 20 kA dump circuit to switch in the two operation modes. Besides this operation the some bus bar connections have to be changed. The 1.8 K test of the LCT coil and the W 7-X prototype coil were performed by the 50 kA power supply and the 20 kA dump circuit [3.4.2-1]. Fig. 3.4.2-2 presents the current and traces of a safety discharge during the test of the W 7-X coil. For the test of the TFMC with the LCT coil, the LCT coil is operated by the 20 kA power supply (Bruker) and the 20 kA dump circuit.

3.4.3 80 kA dump circuit for the TFMC

The modification in the dump circuit of the TFMC consists of two fast closing switches (33.1, 33.2) in parallel in the first short circuit path with the two arc chute breakers 32.1 and 32.2 in series (Fig. 3.4.3-1). The reason is that, for the parallel operation, the short circuit path has to be closed as fast as possible which will be discussed in section 3.4.6. The second arc chute breaker is needed for redundancy reason because a pyro-breaker was not available for 80 kA currents.

During the testing of the 80 kA dump circuit it was found that voltage drop across the short circuit path was to high. The voltage drop of about 27 V across it at 80 kA was in the range of the inverter mode voltage of the power supplies of about 30 V. Therefore a second short circuit path was introduced to reduce the total resistance of the short circuit path and the voltage drop across it. The installed switches 42 and 42.2 in the second short circuit path are of the same type as 32.1 and 32.2. The voltage drop is reduced now to about 17. Simultaneously with this action the breaking capability of the switch S0 was improved by an arc chute switch S0.2 in parallel. The current is first commutated from S0 to S0.2 which finally interrupt.

The separation switches 41.1 and 41.2 disconnect the 80 kA dump circuit from the power supplies for insulation resistance testing and other operation modes of the power supply.

Analogous to the circuit in 3.4.2, the soft grounding will be disconnected in the operation mode "high voltage testing".

The dump circuit parameters for the LCT and TFMC dump circuit are summarized in Table 3.4.3-1.

Table 3.4.3-1 Dump circuit parameters for LCT and TFMC

U: Discharge voltage; I: Coil current; R: Discharge resistor; L: Coil inductance; τ: Time constant if the coil is discharged alone; τ_{eff}: Effective time constant (That means the time needed till the current I is (I_0/e) when both coils are discharged jointly with the time constants given in the table. The influence of the steel case and the radial plates is taken into account.

	LCT	TFMC
U [kV]	2.0	0.536
I [kA]	16.0	80.0
R [Ω]	0.125	0.0067
L[H]	1.57	0.027
τ [s]	12.56	4.0
τ_{eff} [s]	15.4	3.2

3.4.4 Testing of the TFMC by transient voltages

3.4.4.1 The POLO switching circuit for testing transient voltages

The POLO switching circuit was developed in the frame of the POLO project in order to test the poloidal field model coil POLO under operation conditions of poloidal field coils (fast current rise, transient field changes, high voltage loading etc) [3.4.4.1-1, 3.4.4.1-2]. This circuit can be used with slight modification of the dump resistor for the TFMC too. The TFMC can be fast discharged and the rated high voltage loading of the winding is demonstrated. This is a challenging experiment because the radial shear plate type winding has to be considered under aspects different to the usual pancake or layer winding. The fixing of the radial shear plate potential determines the transient voltage properties, e.g., during current commutation procedure in the dump circuit [3.4.4.1-3, 3.4.4.1-4].

The POLO switching circuit contains a counteracting current switch which is similar to that foreseen for the ITER coil dump circuit.

The POLO switching circuit is presented in Fig. 3.4.4.1-1. The POLO switching circuit is connected to the 30 kA power supply. The following operation modes are used for testing the ITER TFMC:

- Safety discharge in case of a quench or emergency
- High voltage discharge for high voltage loading of the TFMC
- High voltage pulse tests for transient voltage loading of the TFMC

  The core of the switching circuit is the counteracting current switch which is a commercial vacuum breaker S2 with reinforced tubes, a 150 µF capacitor bank C and an ignitron valve IGN (Fig. 3.4.4.1-1). The vacuum breaker is in series with an arc chute and a pyro-breaker. The resistor R2 is the high voltage discharge resistor and the resistor R1 is the safety discharge resistor. Both resistors are connected on the one side between S2 and E1 in the branch S2, E1, S1, and on the other side across a pyro breaker EM in series with a vacuum breaker SM to the center terminal of the coil. This path is not used for the TFMC testing so that the vacuum breaker SM is opened, respectively the center high current feed in does not exist. The switches ST isolate the circuit from the power supply during all modes of high voltage operation. The switch SN and a peak voltage suppressor EN protect the power supply against overvoltages. The task of S0 is to interrupt the current path to the power supply and commutate the current to the short circuit path. The different switching operations run down as follows:

- Safety discharge: The power supply is switched in inverter mode, S2 closes and S0 disconnects the power supply by commutating the remaining current into branch S2, S1, E1. The commutation of the current into R1 is performed by opening of S1. In case of malfunction of S1, the pyro-breaker E1 is automatically triggered and performs then the commutation into R1.
- High voltage (HV) discharge: The capacitor bank C is charged to a voltage level controlled by the actual coil current in order to generate the zero transition in the vacuum breaker. After that, the same switching sequence runs down until S0 and ST open. S2 opens and draws an arc.

The counteracting current is initiated by firing of the ignitron IGN. The forced zero transition of the current extinguishes the arc and commutates the current into the resistor R2. Failures (e.g., a not matched capacitor voltage) lead to closing of S2 with the following opening of S1 (safety discharge).

- For the HV discharge also, the time constant for the discharge process of the capacitor bank has to be added. The capacitor discharge acts not only on the short circuit but also on the TFMC. A rise time of about 35 µs was observed during the POLO coil discharge [3.4.4.1-5]. In this case the behaviour is mainly determined by the distribution of the capacitances across the coil. This transient behaviour can be investigated by HV pulsing.
- HV pulsing: A change of busbar connections and the selection of a suitable adapted damping resistor allow a direct discharge of the capacitor bank C into the coil for transient high voltage tests.

The test parameters of the TFMC are summarized in Table 3.4.4.1-1.

Table 3.4.4.1-1: Parameters for high voltage and safety discharge of the TFMC with the POLO switching circuit

TFMC current	21.7 kA
TFMC stored energy at 21.7 kA	6.4MJ
Fast discharge voltage	10 kV
Time constant	0.058 s
Discharge resistor	0.46 Ω
Safety discharge voltage	136 V
Time constant	4.3
Discharge resistor	6.25 mΩ

The POLO switching circuit has equivalent diagnostics like the circuits described above so that the current in the different branches is measured by current transformers and the voltage across the coil as well as across the power supply.

The capacitor bank and the dump resistor need a center grounding in order to have +/- 5 kV across the TFMC which is the equivalent voltage loading like for the ITER TF coils (Fig. 3.4.4.1-2 for HV discharge, Fig. 3.4.4.1-3 for HV pulsing).

Fig. 3.4.4.1-4 shows the ideal potential distribution (no transient voltages) for the high voltage discharge. In this operation mode, the radial plates of the TFMC are connected with the high field joint potential across a resistor. In this ideal case, the voltage drop across each radial is 2 kV and +/- 5 kV across the terminals by center grounding of the discharge resistor.

The analysis of the network model of the TFMC showed that the resonance frequency is in the range of 200 kHz. Therefore internal oscillations are exited for rise times < 1 µs. The TFMC will be not sensitive for the usual switching transients in the 30 µs range. For the validation of the network model, it is of interest to have experimental results. This is the basis for predicting the transient behaviour of the full size TF coils. Some preparing experiments were performed for achieving experimental results [3.4.4.1-6]

3.4.4.2 Circuit for transient voltage tests

The transient voltage tests may be performed at room temperature because the behaviour is purely depending on the temperature. Therefore these tests may be done after warm up (especially the test in the time range which is very time consuming). The basics for the transient voltage tests are given in section 1.4.1 in chapter 1. Presently two circuits are planed and tested with a dummy load.

In addition the normal high voltage dump can also be considered as a transient test but with increased rise time - compared to the following described tests. Therefore a detailed examination of the dump especially during the period between the firing of the ignitrons and the reaching of the maximum voltage is necessary.

3.4.4.2.1 Transient voltage behaviour in the frequency range

Similar to the test with a capacitive dummy load (Fig. 3.4.4.2.1-1) a high frequency generator is applied to the terminals of the ITER TFMC coil. The voltage level at the terminals is about some 100 mV controlled by an oscilloscope. Additionally the second channel of the oscilloscope will be connected with an inner pancake joint potential. The relationship of the maximum amplitudes between the two signals will be measured in the frequency range of about 20 kHz till 500 kHz. Because of the 5 different pancake joints 5 measurement cycles are necessary for each of the 3 cases of connection of the radial plates (connection with the inner pancake joint directly (Fig. 3.4.4.2.1-2) or over a 1.2 MΩ (Fig. 3.4.4.2.1-3) resistor or directly grounded (Fig. 3.4.4.2.1-4)).

3.4.4.2.2 Transient voltage behaviour in the time range

According to Fig. 1.4.1.4-1 in chapter 1 the modified Marx-generator is connected to the terminals of the coil and delivers a bipolar impulse (corresponding to the ±5 kV operation). The damping resistors R_d are stepwise decreased to be sure that the over all voltage of the coil is not oscillating. The modified Marx-generator should generate minimum possible voltage impulses (voltage between terminals about 2.5 kV). The overall voltage between the terminals will be observed by an oscilloscope. The other channel of the oscilloscope is connected with an inner pancake joint potential. The oscilloscope will operate in single sequence mode.

After the bipolar tests unipolar tests should be performed (corresponding to a fictitious +10 kV operation). For this test one stage of the modified Marx-generator will be removed so the resulting voltage will be only about half of the value of the bipolar impulse (about 1.3 kV). After the inception of oscillations along the conductor the test for directly grounding will be stopped to prevent from exceeding the 2 kV value between the grounded radial plate and the conductor at the outermost positive layer.

Because for each of the two voltage forms (unipolar, bipolar) for the three different connections of the radial plates (Fig. 3.4.4.2.1-2, Fig.

3.4.4.2.1-3, Fig. 3.4.4.2.1-4) a sufficient set of data on several points is needed to verify the model in detail at least two weeks will be needed for this test.

3.4.5 Commissioning

The electrical supply system was taken into operation and commissioned as soon as in the experimental programme the opportunity was given to integrate the component to be commissioned in the experimental programme. It has also to be taken into account that realistic operation conditions need always a superconducting inductive load. Some functional checks of the power supplies as well as the dump circuits can be performed with resistive inductive load which is available (Table 3.4.5-1, see also Fig. 3.2.1-2 where the coil can be seen in the front of the TOSKA pit, now positioned in the gap between the TOSKA vacuum vessel wall and the pit wall).

Table 3.4.5-1: Operation parameters of the water cooled resistive inductive load (W 7 OH coil, on loan from IPP Garching. It was constructed as ohmic heating coil in one of the Wendelstein 7)

Voltage	30 kV
Continuous current	20 kA
Resistance	2.75 mΩ
Inductance	7 mH
Magnetic field (center)	47 mT/kA
Weight total	32 t
Inner diameter	1.20
Outer diameter	1.60
Length	4.74 m

The power supply voltage of 30 V limits the current to about 10 kA. The current is additionally reduced by the exponential current decay in tests of the switching circuits or with the switching circuits. The real test current is then in the range of about 6 – 8 kA. A superconducting coil for tests at higher currents is indispensable. Last but not least, the final commissioning tests can only be performed with the original superconducting coil determined for the power supply or switching circuit. A corresponding time has to be provided in the TFMC test programme.

The commissioning was as follows:

- Power supplies : The 30 kA power supply was used for several current lead tests and the POLO coil project. As weak component were identified the primary high voltage transformer coils which had to be exchanged several times caused by insulation damage. It was assured that the engineering design is healthy by pulse voltage tests and partial discharge measurement. External overvoltages of the primary high voltage transformer coils were excluded by overvoltage protection devices. Since all measures did not help to solve the problem, it was concluded to change the transformer system. Today, it is state-of-the-art to use a step down transformer between the 20 kV grid and the rectifier

(20 kV → 400 V → 30 V). In this case a voltage stepping of 20 kV → 1.5 kV → 30 V has to be selected for the existing transformer. The system was installed in spring 1998 and commissioned in September 1998. The 30 kA power supply worked well with this changes during the testing of the W 7-X prototype coil and the commissioning of the 80 kA dump circuit without any disturbances in this field.

The 50 kA power supply was the current source for the test of the LCT coil at 1.8 K , the testing of the W 7-X prototype coil (July 1999) and the commissioning of the 80 kA dump circuit (December 2000). It worked well; no deficiencies were recognized.

The 80 kA power supply (30 kA and 50 kA switched parallel; the control system works in master – slave mode; the control system of the 30 kA power supply works as master) was commissioned by short circuit operation up to 80 kA and also used for the test of the water cooled flexible bus bars of the current leads (section 3.3.4.4). The control circuit operation was tested with the resistive coil described above. Finally it was tested with the inductive superconducting load (POLO coil) up to 22.5 kA [3.4.5-1].

The inverter mode operation needed for current commutation to the dump circuit was tested with the POLO coil and the POLO switching circuit (Fig. 3.4.5-1). The simultaneous ramping up of both power supplies is demonstrated in Fig 3.4.5-2. It was found that the 50 kA power supply shifts its current fraction of the total current to the 30 kA power supply which had to carry now the total current till the short circuit branch S2, S1, E is closed (Fig. 3.4.5-3). Then the current commutates to the short circuit branch. The reason for that is that the voltage of the 50 kA power supply is slightly higher than that for the 30 kA power supply. This will be without consequences as far as the total current is below 30 kA.

An investigation by the supplier was performed (usual operation mode and fault conditions included) whether the components of the 30 kA power supply have the capability to carry also 80 kA for a short time (<

50 ms) [3.4.5-2]. Some changes in the control units and a faster closing switch for the short circuit path were recommended to reduce the unbalanced current distribution during starting of the inverter mode operation. The fast closing switches (6 ms) were already installed in the 80 kA TFMC dump circuit (see Fig. 3.4.3-1). The effectiveness of both measures was demonstrated up to 10 kA operation current during the acceptance test of the 80 kA dump circuit (see below 80 kA dump circuit).

For higher currents, it has to be observed with the TFMC during the testing. Some analysis work is presented in section 3.4.1.

The actual current measurement is performed in the 30 kA and 50 kA power supply by zero flux transformers. During the test of the W 7-X prototype coil it was found that the screening of the zero flux transformer was no longer sufficient [3.1-3], (see also section 3.5.9). The zero flux transformer of the 30 kA power supply showed at about 3.4 mT that the current source for the compensation current was at its outermost limit. This led to an unexpected switch off of the 30 kA power supply by a power supply fault. Since a reliable design of a iron screen was not possible it was decided to add an actual current measurement by shunt resistors for both power supplies. This kind of current measurement is independent of magnetic fields.

The 20 kA power supply needed for the operation of the LCT coil was ordered at the end of 1997. The commissioning has been interrupted by the test of the W 7-X prototype coil. It was success fully completed in December 2000. The change over of the 20 kA dump circuit to the 20 kA power supply was tested and completed in December 2000.

- POLO switching circuit: The circuit was extensively operated during the POLO project. The adaptation for operation with the TFMC is a change of the grounding conditions.
- The 80 kA dump circuit for the TFMC: The circuit was ordered end 1997. Commissioning has been interrupted by the test of the W 7-X prototype coil. It was found during commissioning that improvements

considering the resistance of the short circuit and the switching capability are necessary as already mentioned in section 3.4.3. Current and voltage traces for a manual triggered safety discharge are given in Fig. 3.4.5-4. The current shifting from the higher resistance fast closing short circuit path to second slower closing lower resistance short circuit path can be clearly seen by current traces. Practically no current shifting between the two power supplies took place. In case of a power supply fault in one of the both power supplies a shifting of the current over a time < 50 ms could not be avoided till the short circuit path has been closed (Fig 3.4.5-5, Fig. 3.4.5-6). According to the estimates for fault conditions it is acceptable [3.4.1-1].

3.4.6 Insulation diagnostic by partial discharge measurement

Partial discharge measurement is a destruction free insulation diagnostic tool [3.4.6-1], [3.4.6-2]. According to chapter 1.4.2 on ITER TFMC the ground insulation and the conductor (winding) insulation will be examined. In addition it may be possible to measure the partial discharge activity between radial plates. Because it was found that for different voltage forms the measured apparent charge is in relationship with the peak-peak value the suitable values for the different tests are given according tab. 3.4.6-1.

Tab. 3.4.6-1: Voltages for the different partial discharge tests.

	$U_{peak\text{-}peak}$ / kV	U_{rms} / kV
Ground insulation	5.00	1.77
Conductor / winding insulation	1.00	0.354
Insulation between radial plates	1.00	0.354

After the assembling of the TFMC with the inter-coil structure (ICS) the measurement of the partial discharge activity during the final AC test on ground insulation at 3.54 kV can be performed. It is recommendable to perform also a final conductor test which gives the opportunity to measure the partial discharge on one radial plate for one minute at higher AC voltage.

The suitable high voltage AC equipment of the Cryogenic High Voltage Lab of the ITP is given in Table 3.4.6-2.

3.4.6.1 Partial discharge circuit for ground insulation tests

Fig. 3.4.6.1-1 shows the ITER TFMC arrangement for the measurement on ground insulation. The radial plates are connected with the inner pancake joints over 5 HV connectors. Each connector consists with a Gore high voltage instrumentation cable with 2 plugs suitable for the sockets of the warm vacuum vessel feedthroughs. Because all the radial plates and the conductor are on same potential fuses or resistors are unnecessary. The detection impedance lies in series with the coupling capacity (Fig. 1.4.2.2-1b, Chapter 1) because it is not reasonable to ground the entire case over the detection impedance Z. The impedance Z not only limits the short circuit current but also reduces external disturbance and prevents that the apparent charge bypasses the coupling impedance. Therefore it is very important to use it during partial discharge measurements and have the highest possible value. The four parallel resistors of 50 kΩ limit the short circuit current to about 142 mA.

3.4.6.2 Partial discharge circuit for conductor insulation tests

Fig. 3.4.6.2-1 shows the ITER TFMC arrangement for the measurement on winding / conductor insulation. The examined radial plate is connected with ground potential over the detection impedance, the other radial plates are directly grounded. The grounding connectors of the radial plates have no high voltage insulation and it is not necessary to have high voltage plugs on this connectors. The feedthroughs which are connected with the conductor (high voltage) potential must be closed with blind plugs. The screws of the plugs must be tightened with 30 Nm.

The coupling capacity is directly grounded (Fig. 1.4.2.2-1a, Chapter 1). So it is possible to reduce the value of Z because the apparent charge is not able to bypass the detection impedance. Because of the low capacitive impedance of the coil (C is about 1.8 µF) the resistor is decreased to about

386.5Ω . In this case the safety elements of the control desk switch off the voltage in the case of a short circuit.

Tab. 3.4.6-2: AC high voltage equipment for ITER TFMC

Part	Type	Specification
HV-transformer	REO WTE 50 S	S = 50 kVA, U = 5 kV
Transformer	REO RTMOK	S = 16 kVA, U = 0 ... 230 V
Power Supply (alternatively to transformer)	Spitzenberger & Spieß EP 2250/C	S = 2,25 kVA, U = 0 ... 270 V
Control desk	IEH	
Capacitive compensated voltage divider	Hilo-Test HVT - 40 RCR	U = 30 kV
Capacitive compensated voltage divider	Hilo-Test HVT - 120 RCR	U = 90 kV
Multimeter	DP 100	
Capacitive voltage divider	MWB CP100	U = 100 kV, 37 pF
Coupling capacity	Haefely KK 100 - 1	100 kV, 1 nF
Resistor	MWB	R = 50 kΩ P = 125 W
Resistor	Schniewindt	R = 50 kΩ P = 250 W
Resistor	MWB	R = 245 kΩ P = 60 W
Resistor	MWB	R = 132 Ω P = 60 W
Detection impedance	ITP TE 1	
PD measurement system	PD ICM	
Oscilloscope	Tektronix 2430 A	
Calibrator 5 pC, 100 pC	Haefely 451	
Calibrator 1 nC, 10 nC	PD CAL1B	
5 HV connectors	RLV 001 - 006	U_{test} = 9.9 kV
4 grounding connectors		
1 connector for detection impedance		
5 blind plugs	WHB	U_{test} = 9.9 kV

3.4.6.3 Partial discharge circuit for insulation tests between radial plates

In Fig. 3.4.6.3-1 a circuit for partial discharge measurements between radial plates is shown. The examined plate is grounded over the detection impedance (fig. 1.4.2.2-1a). Because it is very likely that the partial discharge activity from radial plates to ground insulation is lower than to the conductor the other plates are connected with the high voltage conductor potential. So 4 high voltage connectors for the warm feedthroughs are needed. The feedthrough of the inner pancake joint of the examined radial plate is covered by the blind plug. To examine all radial plates in this way five measurements are necessary.

3.4.7 TFMC power system model validation and prediction at 80 kA

3.4.7.1 Introduction

A computer model of the TOSKA power system for the testing of TFMC, whose basic circuit diagram is shown in Figure 0-1, has been developed with SIMULIK[1], using the Power System Blockset (PSB) toolbox [3.4.7-1]. The PSB library includes:

- ☐ Electrical Source blocks that generate electric signals
- ☐ Linear and non-linear network elements
- ☐ Power electronic devices
- ☐ Electric machinery models (e.g., three phase transformers)
- ☐ Connector blocks
- ☐ Measurement blocks for the current and voltage measurements.

The model, called tfmcps, includes a DC equivalent model for the 30 and 50 kA power supplies, the current controller and a switching network representing the new 80 kA dump circuit (see Figures 0- 2, 3 and 4). More details on the tfmcps model can be found in [3.4.7-2]. The current version, tfmcps6, uses six state variable for the electric network and an additional state variable for every switching element. The busbar resistances used in the model have been derived from measurements. For the busbar inductances only computes values are available. With the assumptions

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[1] Simulink is a software package, distributed by MathWorks Inc, for modeling, simulating, and analyzing dynamical systems using MATLAB as computational engine. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two.

made, the eigenvalues of the network state matrix are: 1.0e6 * [-6.2756, -1.3451, -0.8375, -0.3343, -0.0257, -0.0004]. The make switches are modeled with as an inductor (L_{on}) and a resistor (R_{on}) connected in series with an Ideal Switch. The circuit breakers, instead, have been modeled as an inductor (L_{on}) and a resistor (R_{on}) connected in series with a Gate Turn-Off (GTO) thyristor [3.4.7-1]. The ratio L_{on}/R_{on} for the various switching elements has been assumed between 5 and 10ms.

After validation the model will be used for:

- Circuit analysis in normal and fault condition.
- Prediction at 80 kA.

3.4.7.2 Model validation

The model has been validated experimentally using the transient data of TOSKA recorded during the acceptance tests with a dummy Cu Coil (W7-OH) performed on the 21st December 2000. The shot that will be presented here (# 97110) is referred to a Safety Discharge (SD) at 10 kA triggered manually from the Dump Circuit (DPC) local control panel (see Figure 0-5).

The simulation has been performed, as it occurs in the real system, with a controlled ramping up of the current up to 10 kA (0 - 12s) followed by the trigger of the SD after that the steady state condition is reached. The safety discharge timing sequence is given in Table 0-1.

The comparison between the power supply currents (CIL30 and CIL50) and the equivalent outputs of the model are shown in Figure 0-6. Figure 0-7 shows instead the current flowing in the fast crowbars (CIS1-80), in the slow crowbar (CIS2-80) and in the dump resistor (CIR80) versus model outputs. The differences, mainly during transients, are thought to be due to the network inductances that need to be checked experimentally or by calculation using the actual geometry of the busbars.

Table 0-1: Safety Discharge timing sequence. The times are referred to the trigger time of the data acquisition, which is assumed as t=0.

Time(ms)	80 kA dump circuit switching sequence
33	Simultaneous "inverter mode" command to the 30 and 50 kA power supplies
48	Fast make switch S1.1 closed
93	Slow make switch S1.2 closed
190	Power supply bypass switches Sn1 and Sn2 closed
274	Dump resistor make switch S3 closed[2]
330	30 kA power supply isolation switch S0.1 open
350	50 kA power supply isolation switches S0.2 open
590	Circuit breakers S2.1 open
680	Circuit breakers S2.2 open

3.4.7.3 Prediction at 80 kA

After the validation, the model has been used to simulate a current ramp up followed by a safety discharge at 80 kA of TFMC. The current reference used for the ramp up is shown in Table 0-2. Some results of the first 2.5s of simulation are shown in Figure 0-8. An oscillation with a period of about 0.7s and damping of 0.3 is present on the power supply output voltages. The oscillation is present also on the currents but with much lower amplitude. The same signals for the full current ramp (0 - 120s) is shown in Figure 0-9. In order to reach smoothly the steady state conditions the di/dt has been gradually reduced before reaching the flattop. Figure 0-10 shows the safety discharge, performed with the same time sequence of Table 0-1.

Table 0-2: Current reference used during current ramp up to 80 kA

Time (s)	0.05	2	108.	112	116	118	120

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[2] This is an assumption for the simulation since, at present, is not possible from the available measurements to identify the exact closing time.

I_{ref} (kA)	0	1.6	76	78.4	79.6	80	80
dI/dt (A/s)	821	702	600	300	200	0	0

Figure 0-11 shows the current flowing in the isolation switches S01 and S02 (see Fig. 0-3) and the voltage across the switches during opening[3] Both breakers are designed to interrupt the nominal current (i.e., 30 and 50 kA respectively) and there should be no problems. Figure 0-12 shows the same quantities in the case of only the fast crowbar is activated. The currents to interrupt are accordingly bigger but also in this case there should be no problem. Figure 0-13 show that also in this case the safety discharge can be performed within the same time scale. The time required to transfer the current into the crowbar in this case is about 50 ms longer due to the higher resistance of the circuit.

3.4.3.4 Further developments

The activities foreseen in the near future and during the power supply commissioning with TFMC coil are the following:

- Calculate circuit inductance and check with the switch manufacturer the values of the ON resistor and inductor. Improvement of the model during the early phase of the safety discharge.
- Compare current ramp transient and optimize control parameters.
- Check calibration of voltage and current measurements. Consistency checks.
- Simulate different fault conditions on the DC side.
- Implementation and test of the AC components (e.g, three phase transformers and full thyristor bridges) for the simulation of faults in the AC side.

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[3] This is only the beginning of the "manoeuvre" of opening (contact separation). It takes between 150 to 200 ms for the switches to open completely. Only after they are fully open the commutation of the current into the dump resistor can be initiated.

- Implementation and test of the AC components (e.g, three phase transformers and full thyristor bridges) for the simulation of faults in the AC side.

3.4.8 References

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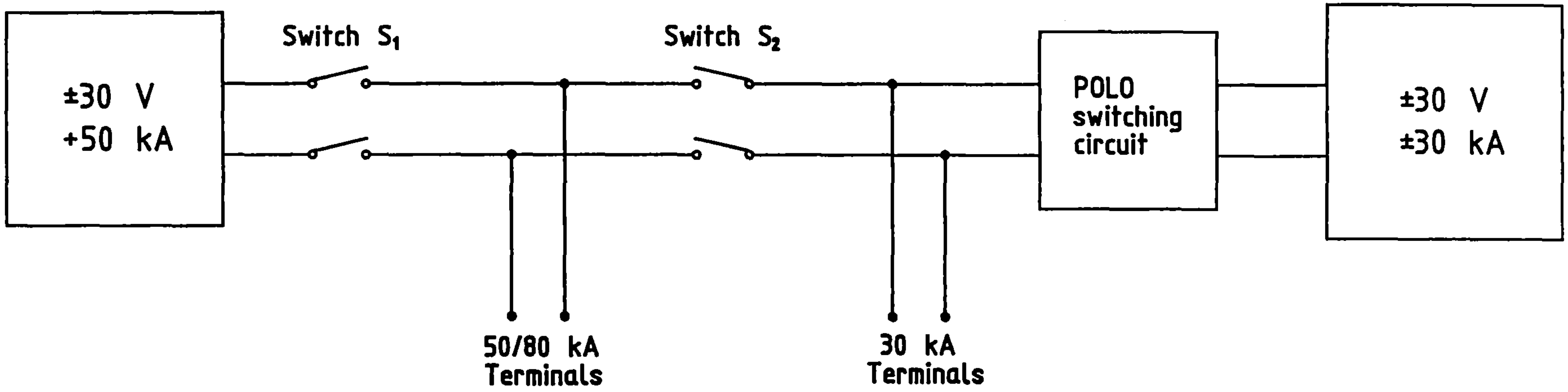


Fig. 3.4.1-1: The busbar connections of the 50 kA and 30 kA power supply of the TOSKA facility. The power supplies can be isolated from the busbar by separation switches S_1 (50 kA) and another one integrated in the POLO switching circuit (30 kA).

The switch S_2 separates the power supplies for single mode operation.

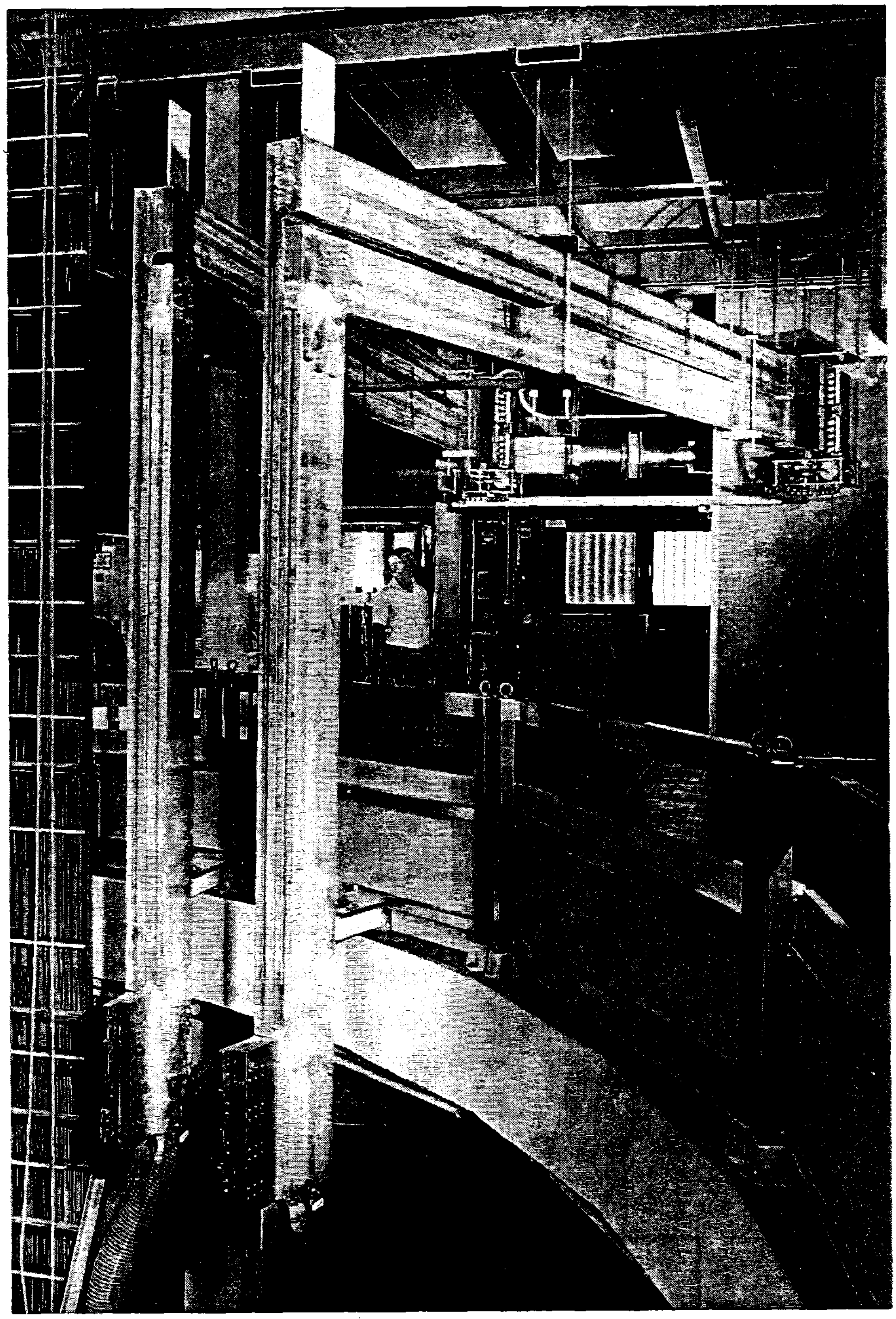


Fig. 3.4.1-2: The 50 kA bus bars with the separation switches (S_1, Fig. 3.4.1-1) and the power supply in background

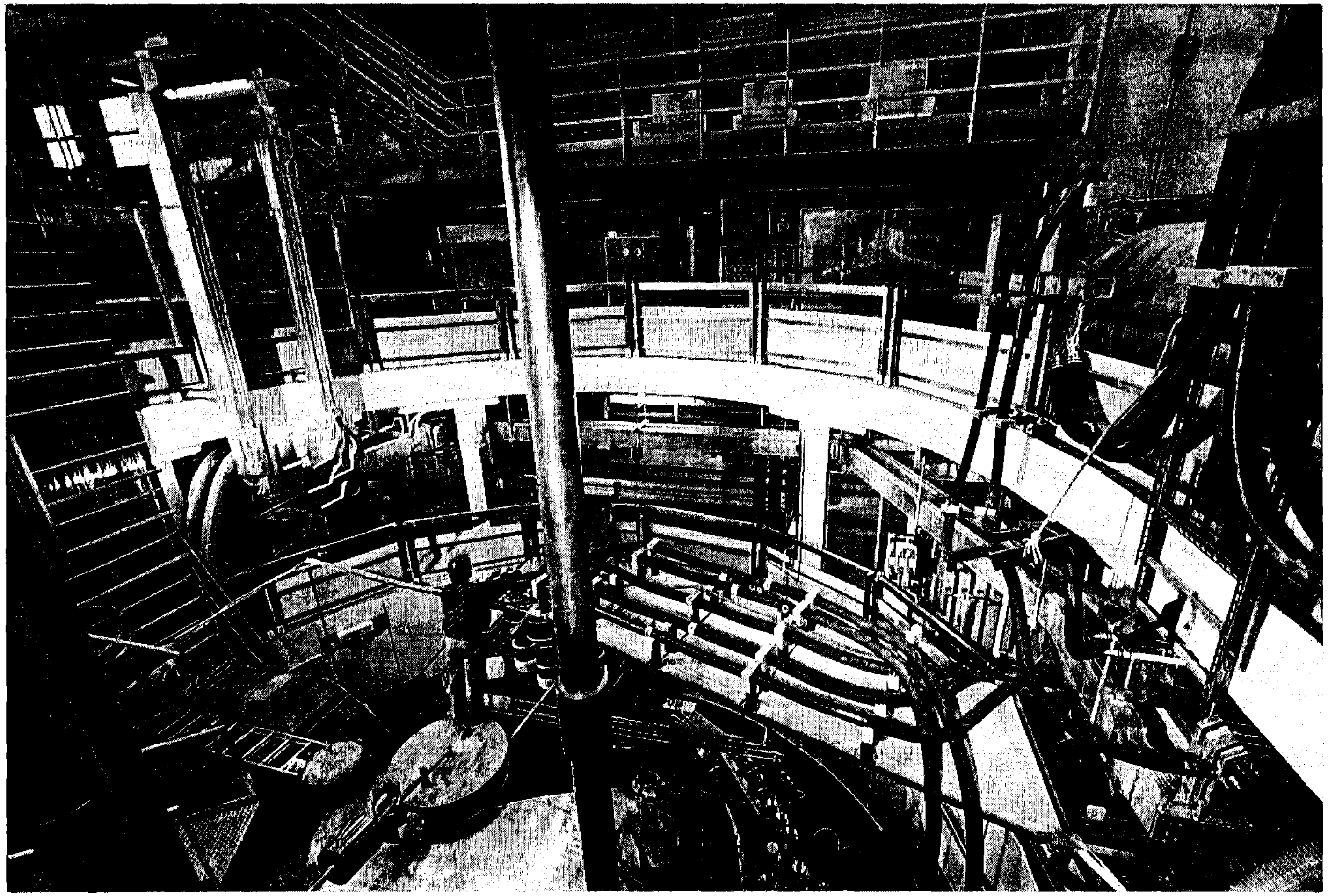


Fig. 3.4.1-3: The Al busbars at the bound of the TOSKA pit connecting the 30 kA (right) with the 50 kA power supply (left). In front, the vacuum vessel with the water cooled cables and current lead warm ends during the POLO coil testing.

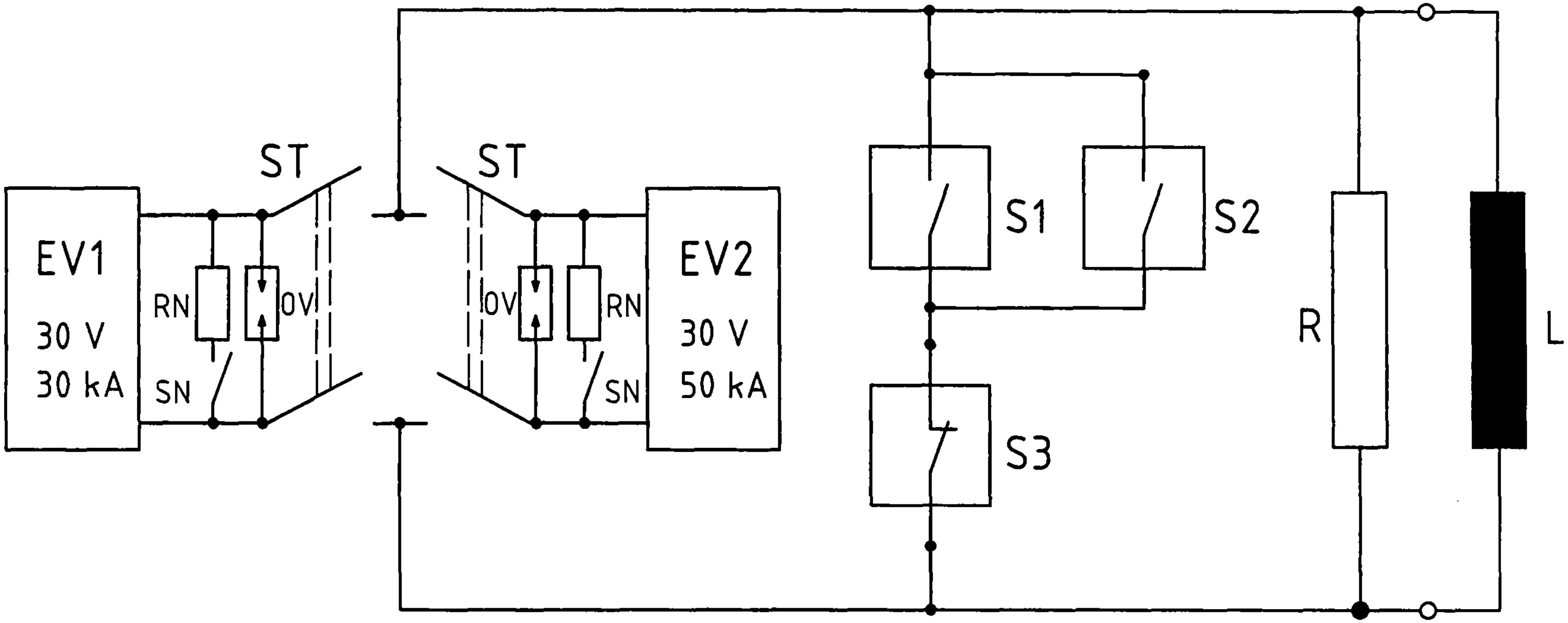
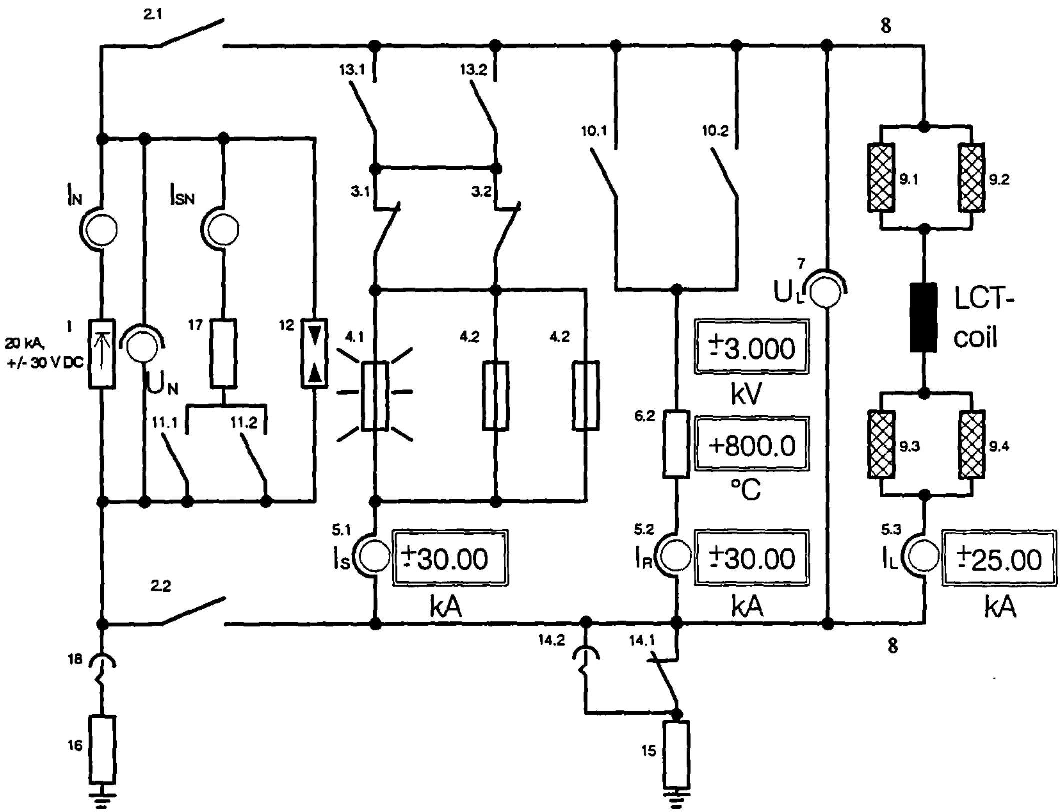
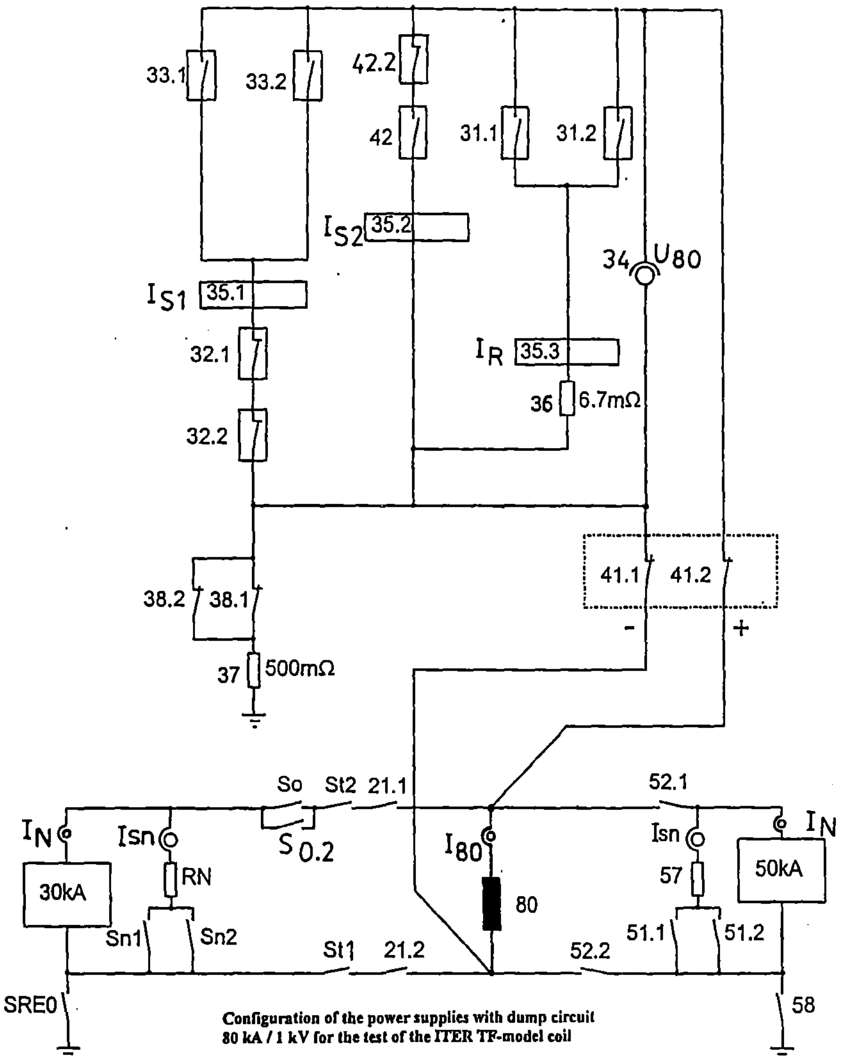


Fig. 3.4.1-4: Basic scheme of the dump circuits used in the TOSKA facility discussed for the TFMC circuit with the 80 kA power supply (EV1, EV2 high current power supplies; RN current limiting resistor; OV overvoltage protection; SN closing switch; S1, S2, S3 arc chute breakers; R dump resistor; L superconducting coil)



1	Power supply 20 kA, +/- 30 V DC
2.1 / 2.2	(Isolation) switch 25 kA, 50 V
3.1 / 3.2	Breaker 15/12 kA, 3 kV
4.1	Pyristor switch 4.5 kA, 2 kV
4.2	Fuse 200 A, 3 kV AC
5.1 / 5.2	Current transformer +/- 30 kA (+/- 60 kA)
5.3	Current transformer +/- 25 kA (+/- 60 kA)
6.2	Charge/discharge resistor 125 mOhm, 320 MJ
7	Voltage transformer 3 kV (3.2 kV)
8	Bus bars 20 kA, 6 kV
9	High current cables (each polarity: 2 x 13.5 kA), cooled by desalinized water
10.1 / 10.2	Switch 1 kA, 690 V
11.1 / 11.2	Switch 1 kA, 1 kV
12	Overvoltage protection 900 V, 1 kA for 1 sec
13.1 / 13.2	Switch 1 kA, 1 kV
14.1	Earthing relay
14.2	Earthing connector 1 kA, 6 sec
15 / 16	Earthing resistor 2 Ohm, 20 MJ
17	Limitation resistor 1 - 9 mOhm, 15 MJ
18	Earthing connector 1 kA, 6 sec

Fig. 3.4.2-1: Dump circuit of the LCT coil test designed for dumping 300 MJ with a peak power of about 50 MW



Configuration of the power supplies with dump circuit
80 kA / 1 kV for the test of the ITER TF-model coil

80	ITER-TFMC (27 mH)
30 kA	Power supply (+/- 30 kA, +/- 30 V DC)
50 kA	Power supply (+ 50 kA, +/- 30 V DC)
31.1 / 31.2	Switch (80 kA for 2 sec)
32.1 / 32.2	Breaker (active as 1. Short-circuit path: 80 kA for 2 sec, 1 kV)
33.1 / 33.2	Fast closing switch (80 kA for 2 sec)
34	Voltage transformer (+/- 1 kV DC)
35.1 - 35.3	Current transformers (each for +/- 80 kA DC)
36	Dump resistor (6.7 mΩ, 100 MJ)
37	Grounding resistor (500 mΩ, 5 MJ)
38.1	Grounding switch (1.2 kA, 600 V)
38.2	Grounding relay (100 A, 85 kV, 1 kA minimum for 1 sec)
41.1 / 2	Isolation switch (80 kA for 2 sec, 10 kV)
42 / 42.2	Breaker like 32.1 / 32.2 (active as 2. Short-circuit path) (originally foreseen as: 1. Double redundancy for commutation 2. arc protection of isolation switches St1 / St2, 52.1 / 52.2)

SN1 / SN2, 51.1 / 51.2	Short-circuiting switches 1 kA, 1 kV
RN, 57	Limitation resistors (RN: 22.95 mΩ, 57: 13.8 mΩ)
SRE0, 58	Grounding connectors
S0	High current separation switch (35 kA, 3 kV)
S0.2	Breaker (80 kA for 2 sec, 1 kV)
ST1 / ST2	Isolation switch (30 kA, 24 kV)
52.1 / 52.2	Separation/Isolation switch (50 kA, 1.5 kV)
21.1 / 21.2	Disconnector for single operation of the Power supplies(30 kA, 1.5 kV)

Fig. 3.4.3-1: Technical version of the TFMC dump circuit described already in scheme in Fig. 3.4.1-4

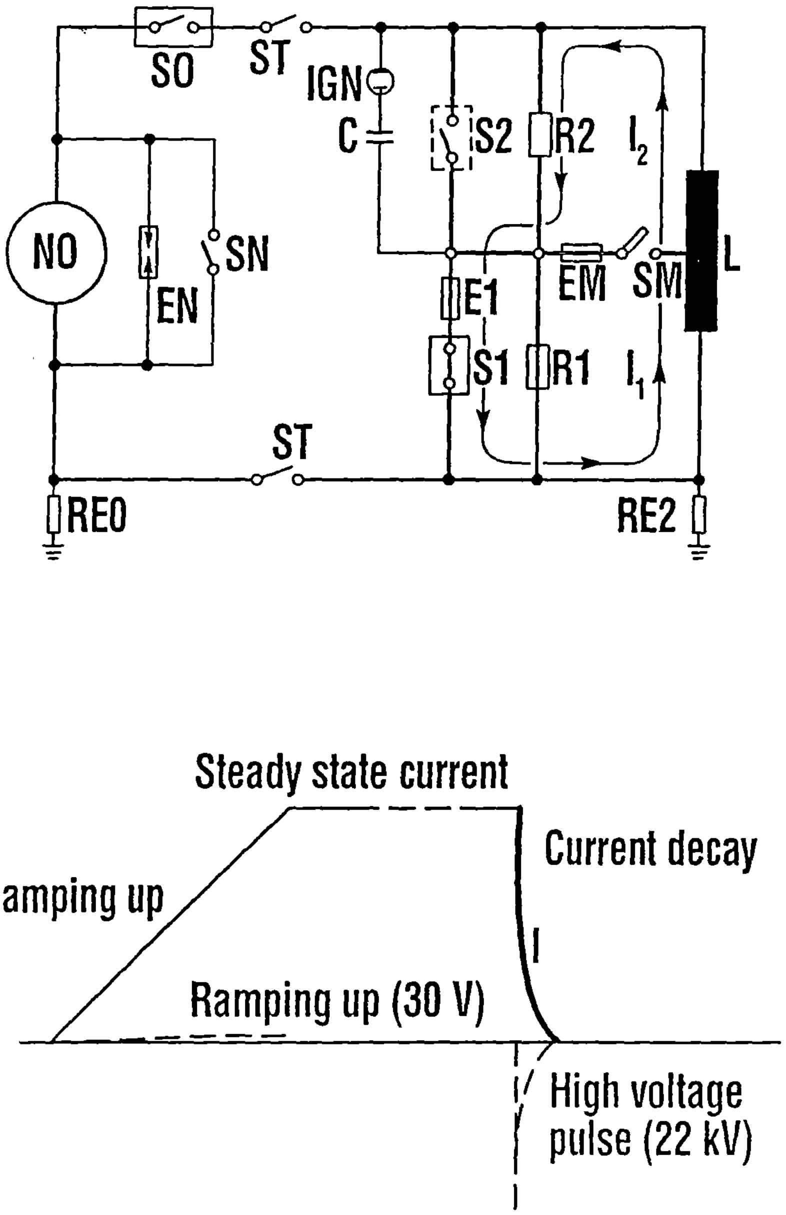


Fig. 3.4.4.1-1: The POLO switching circuit with a counteracting current switch for generating the high voltage loading across the TFMC

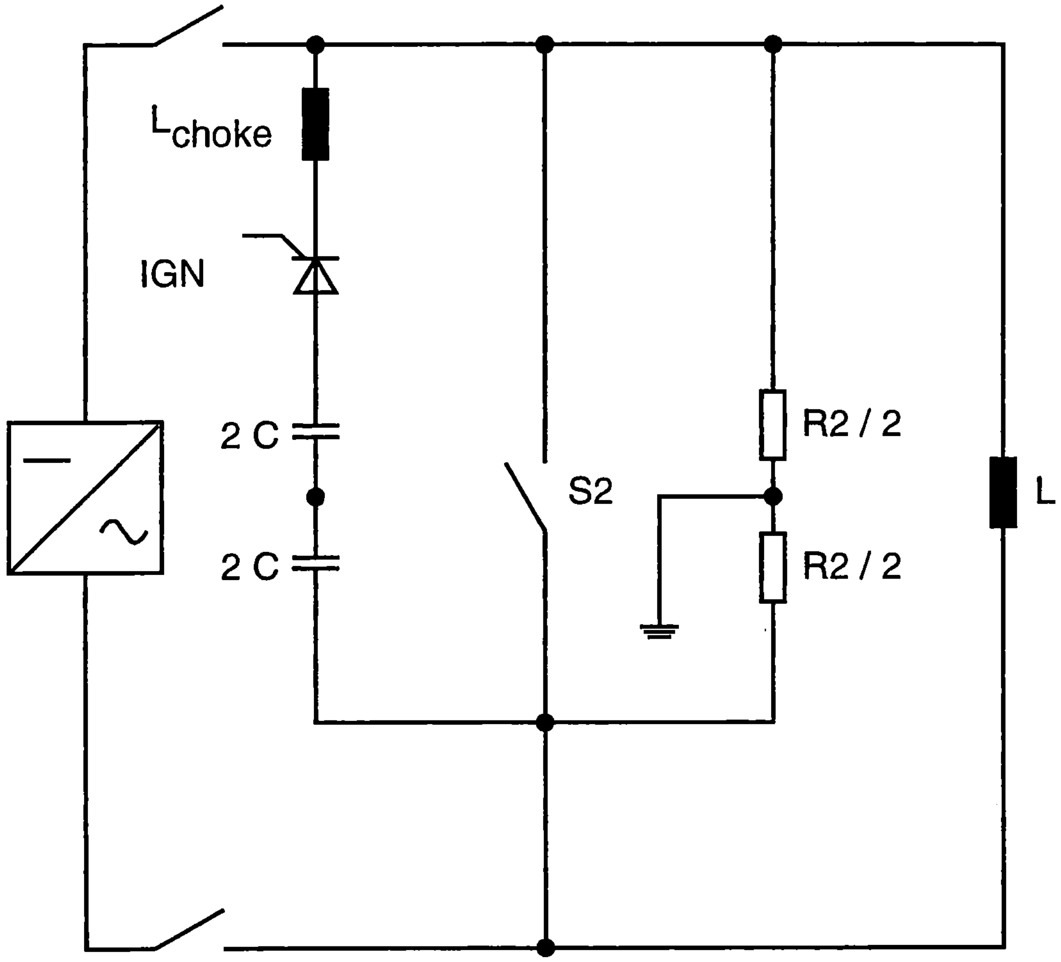


Fig. 3.4.4.1-2: Simplified circuit for the HV discharge with center grounding and a +/- voltage across the coil terminals

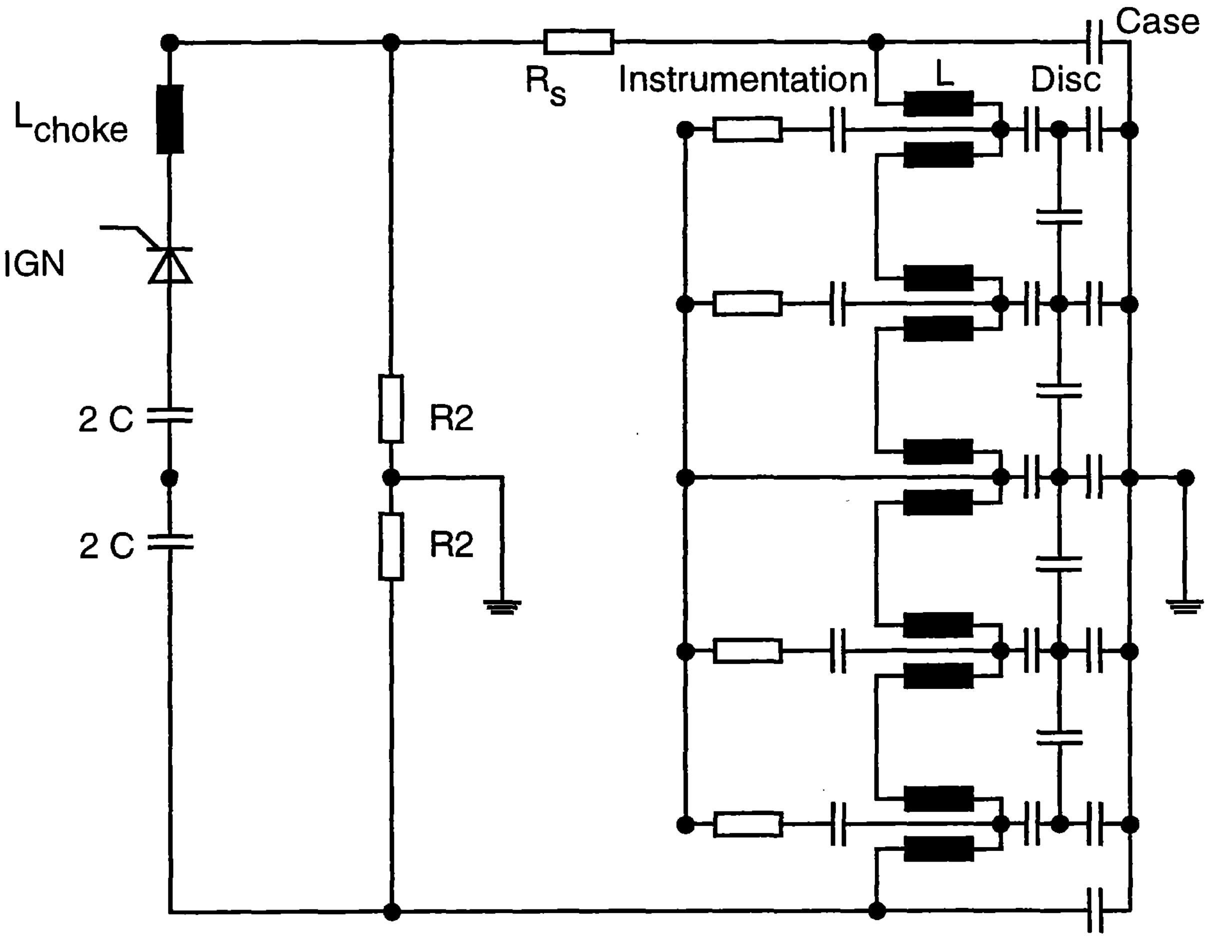


Fig. 3.4.4.1-3: Simplified circuit for pulse voltage tests with center grounding and +/- voltage across the terminals. A simplified network of the TFMC is indicated.

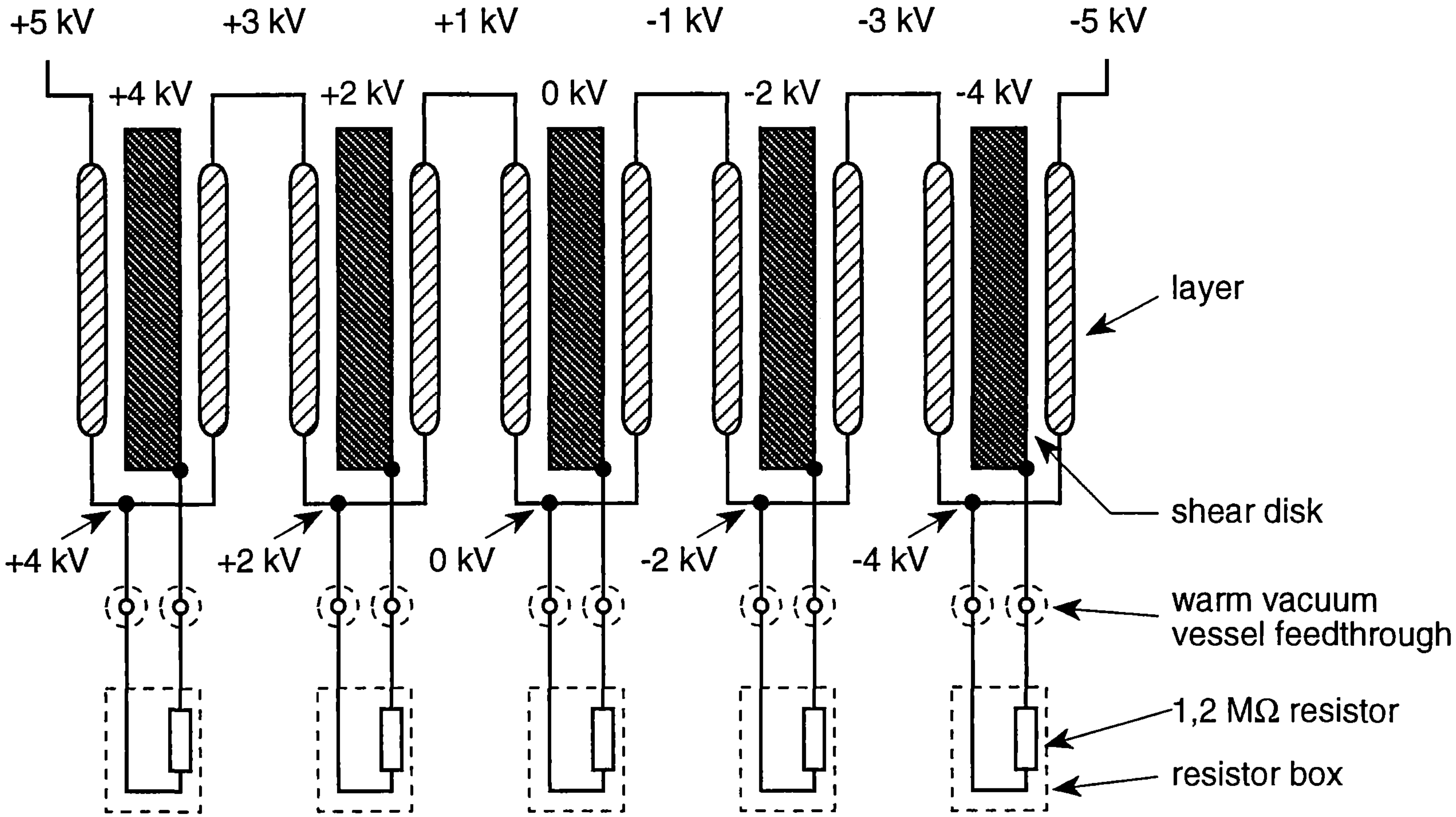


Fig. 3.4.4.1.-4: The ideal voltage distribution across the TFMC if the shear plate potential is connected to the high field joint across a current limiting resistor.

Fig. 3.4.4.2.1-1: High frequency test with dummy load representing the impedance of the coil

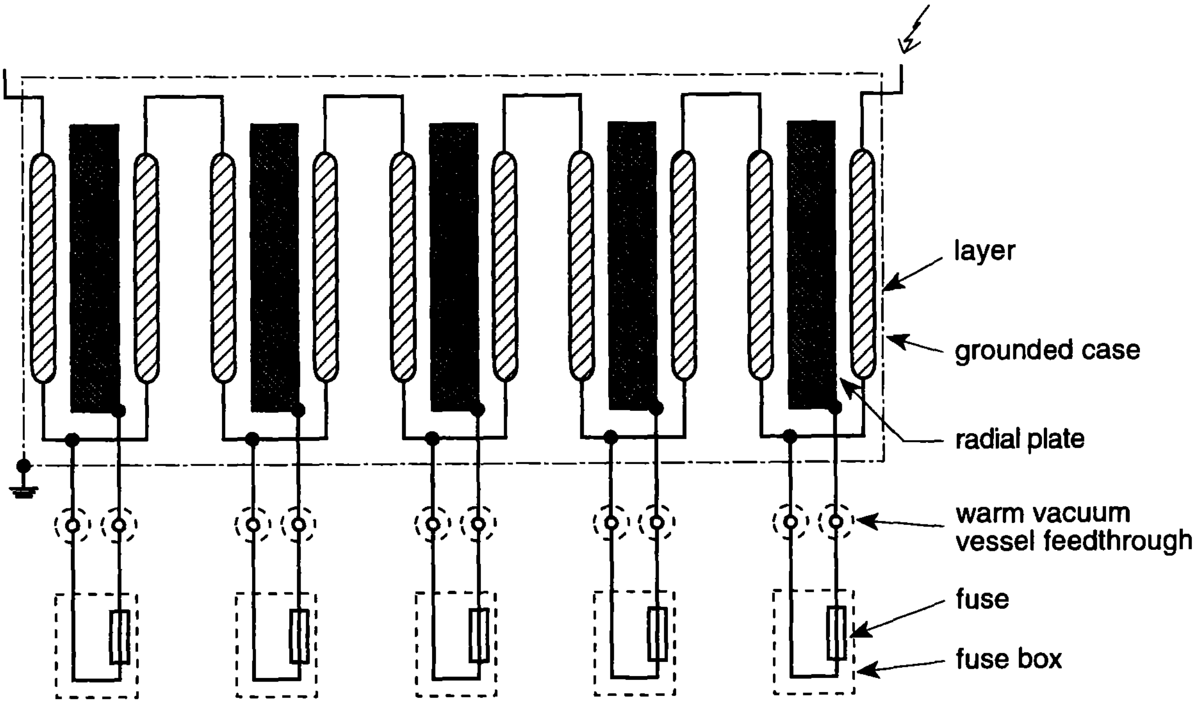


Fig. 3.4.4.2.1-2: Normal operating mode arrangement of ITER TFMC with direct connection of the radial plates to the inner pancake joints across fuses

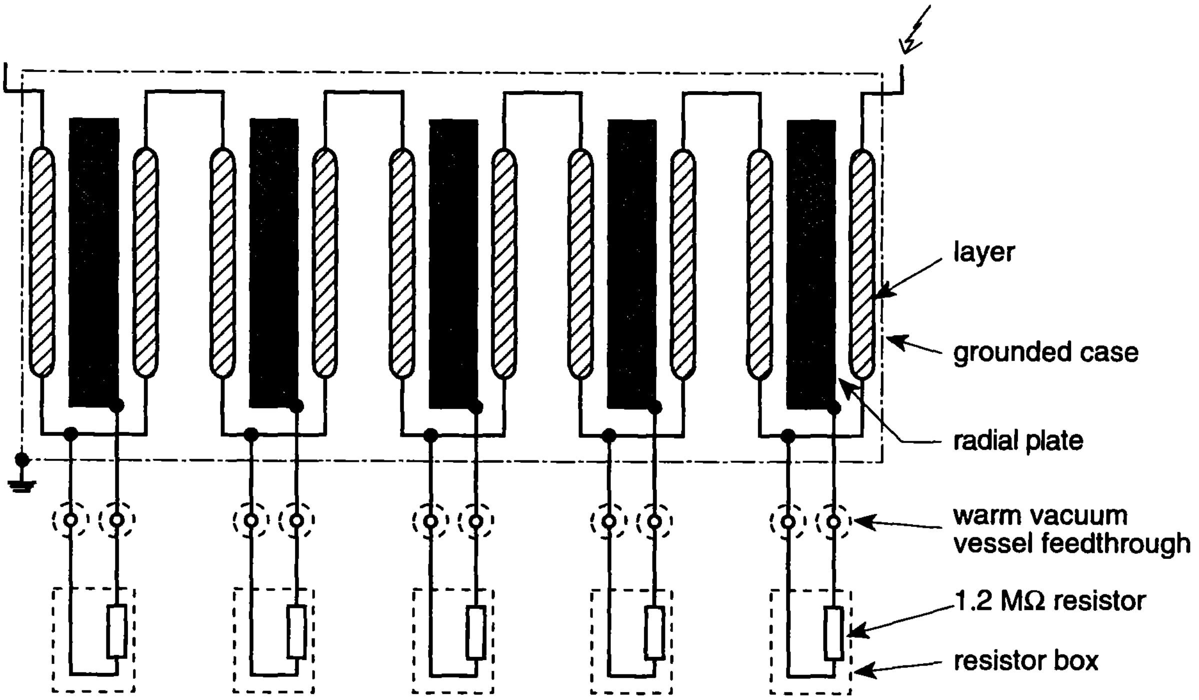


Fig 3.4.4.2.1-3: Normal operating mode arrangement of the ITER TFMC with connection of the radial plates to the inner pancake joints across resistors

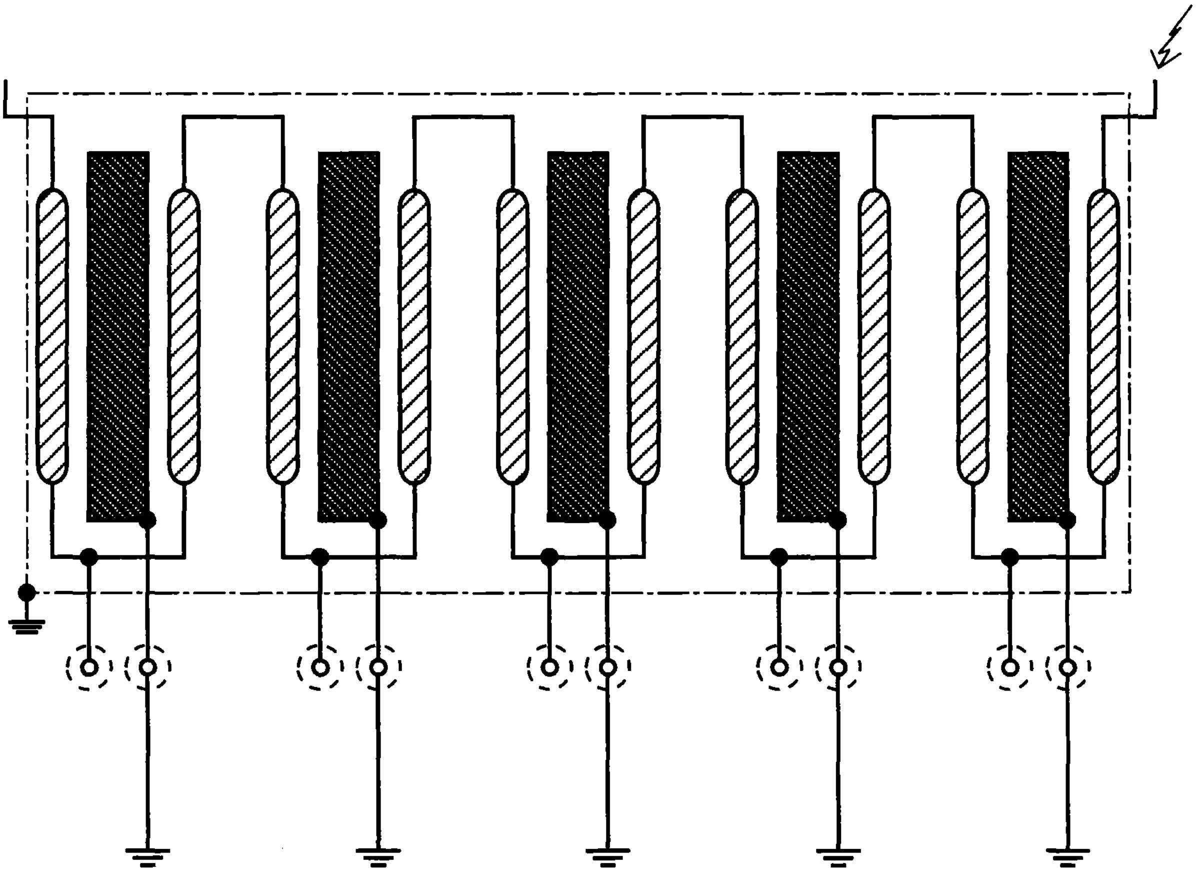


Fig. 3.4.4.2.1-4: Arrangement of the ITER TFMC with directly grounded radial plates

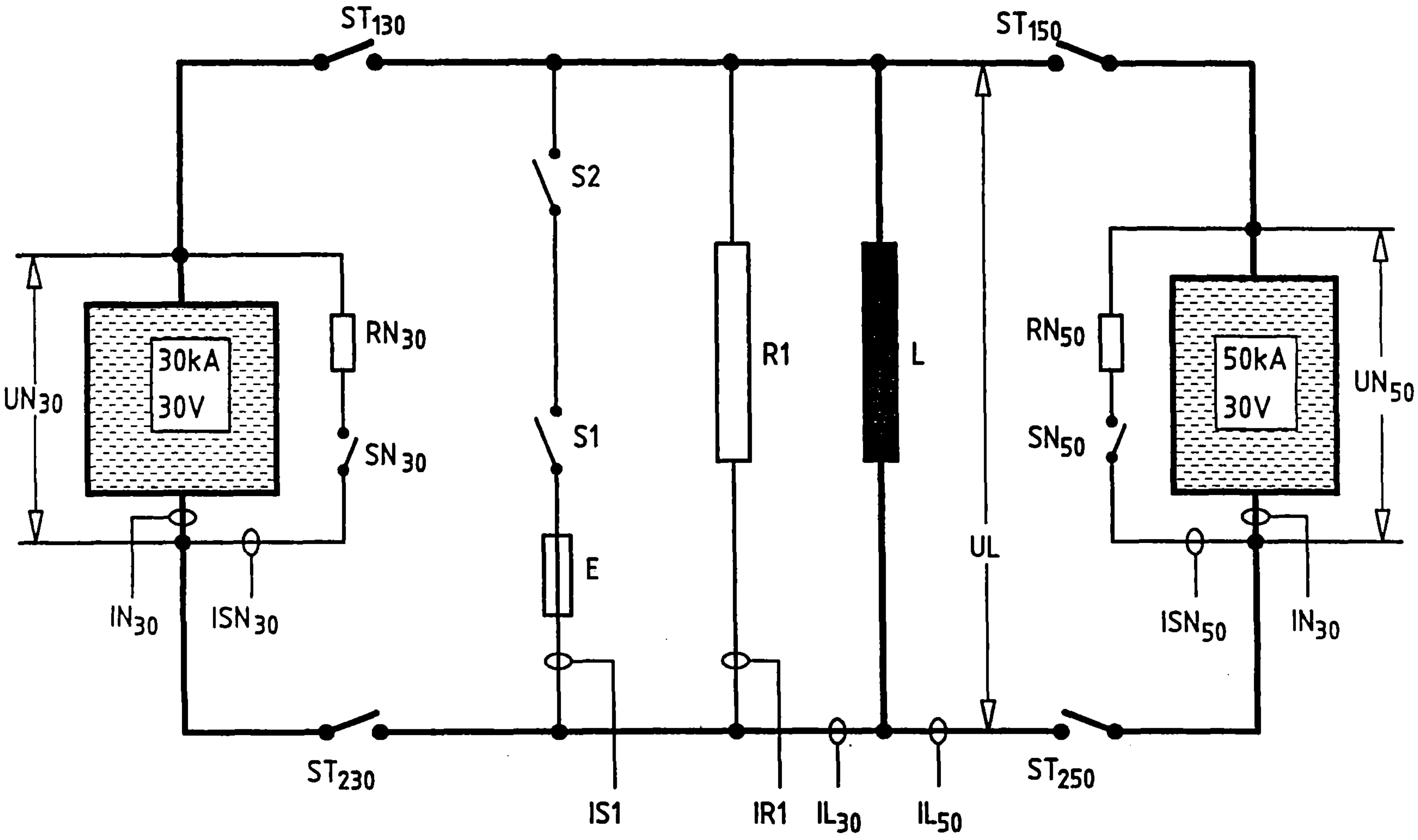


Fig. 3.4.5-1: Circuit for testing of the parallel operation of the 30 kA and 50 kA power supply with the POLO coil and the POLO dump circuit (R: resistors, S: switches, I: current transformers, L: POLO coil, E: pyro-breaker)

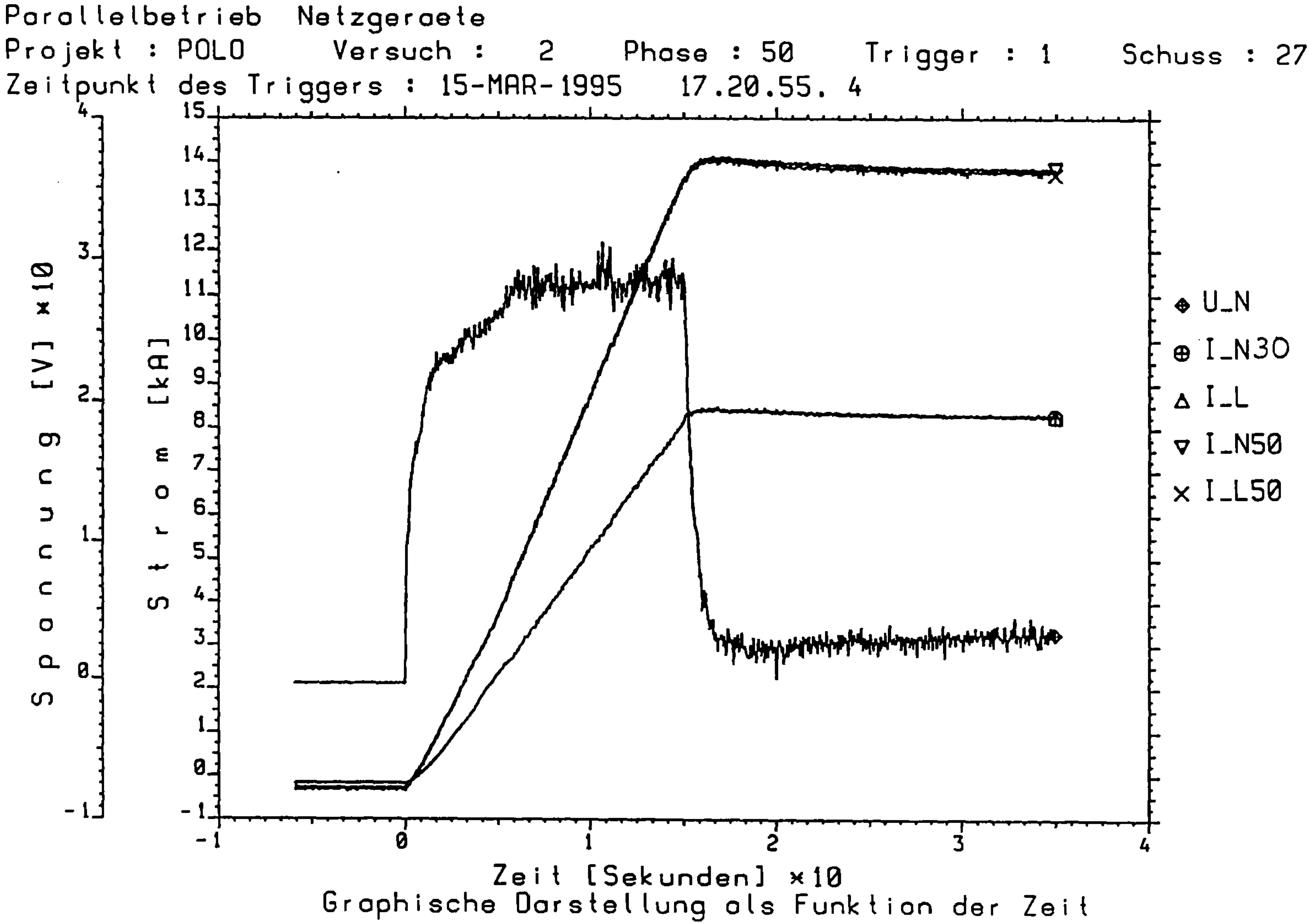
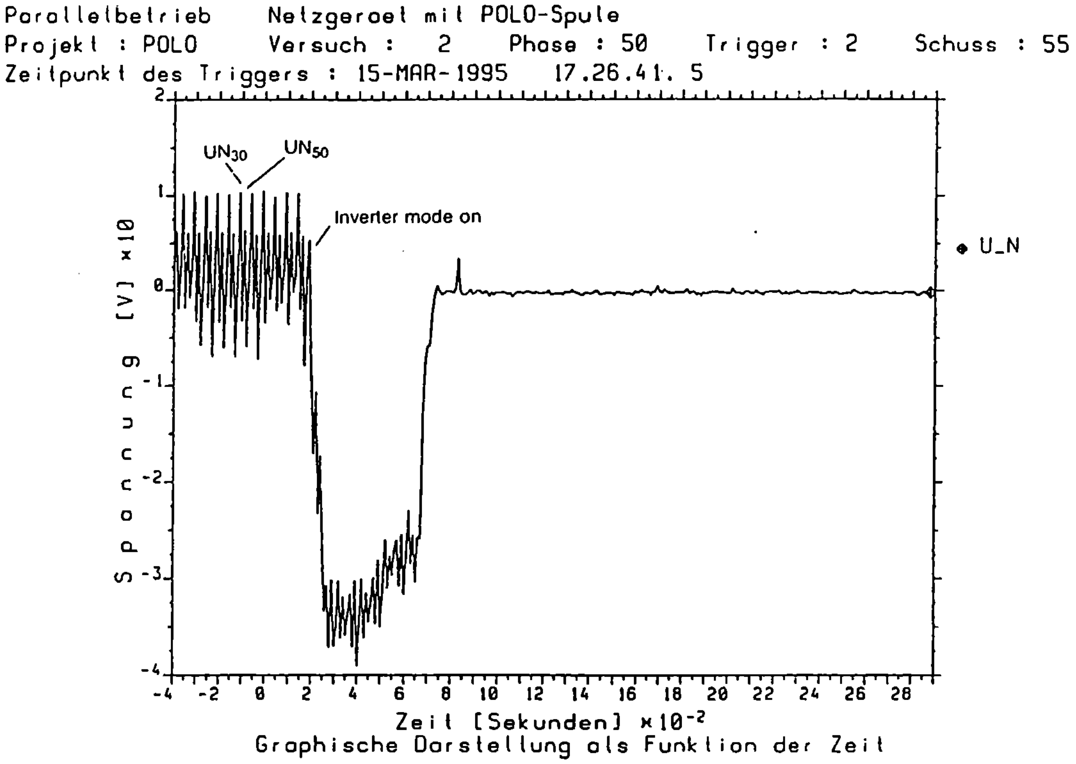


Fig. 3.4.5-2: The current of the 30 kA as well as the 50 kA power supply and the voltage during ramping up of the POLO coil



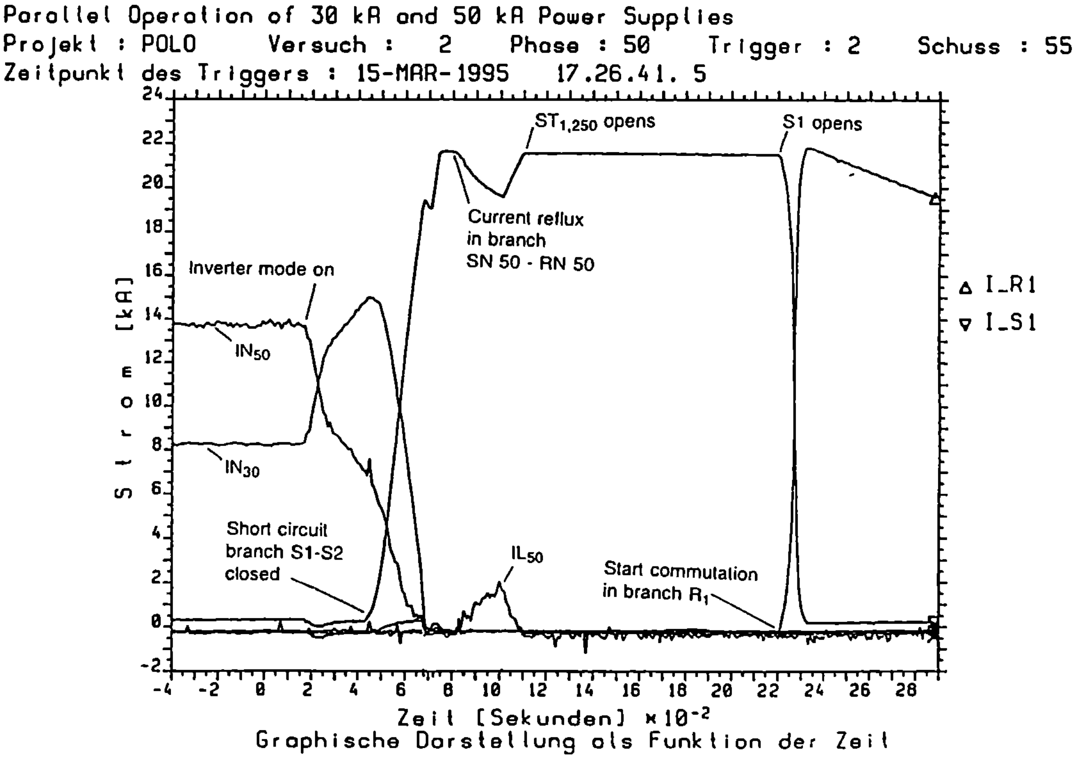


Fig. 3.4.5-3: Voltage and current traces in the dump circuit during a dump triggered by a fault in the 50 kA power supply. The traces show the shifting of the sum current IN_{30} to the 30 kA power supply until the short circuit branch S1, S2 closes.

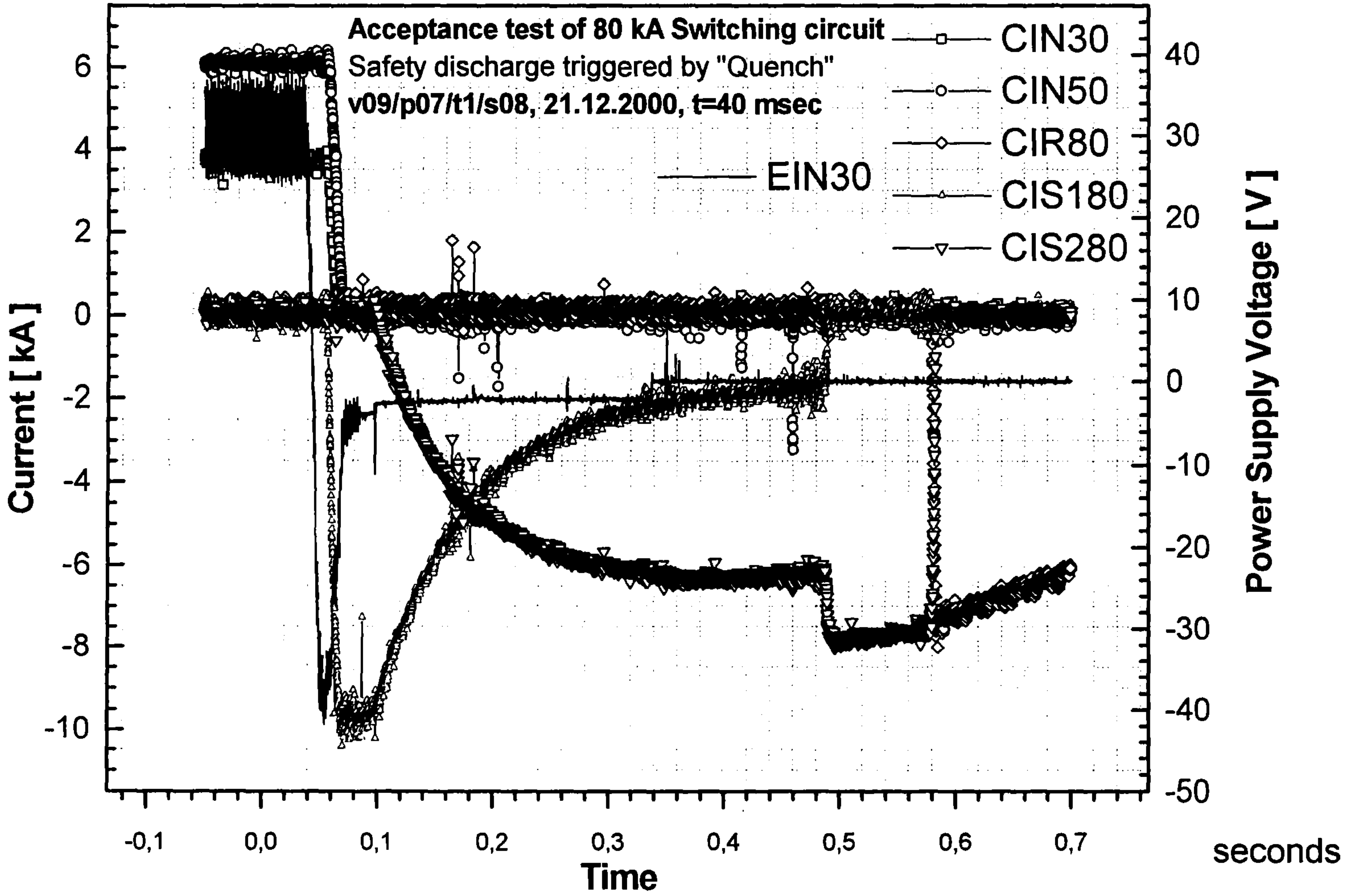


Fig. 3.4.5-4: Voltage and current traces during a safety discharge using the 80 kA power supply and the 80 kA dump circuit released by manual triggering. (EIN30: Voltage of the 80 kA power supply; CIN30: Current of the 30 kA power supply; CIN50: Current of the 50 kA power supply; CIR80: Current through the dump resistor; CIS180: Current through the fast closing short circuit path; CIS280: Current through the slow closing short circuit path.

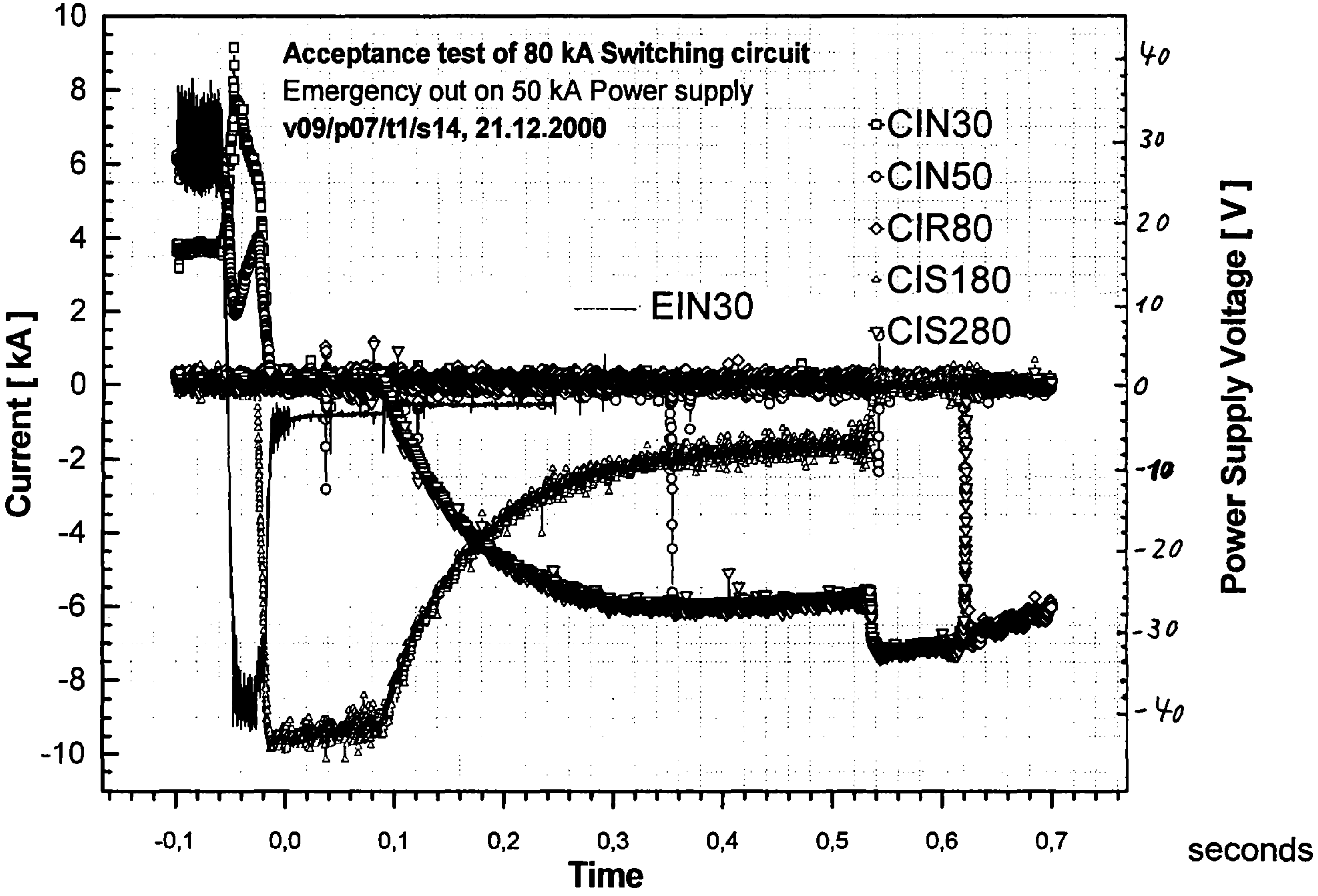


Fig. 3.4.5-5: Voltage and current traces during a safety discharge using the 80 kA power supply and the 80 kA dump circuit released by switch off of the 50 kA power supply. (EIN30: Voltage of the 80 kA power supply; CIN30: Current of the 30 kA power supply; CIN50: Current of the 50 kA power supply; CIR80: Current through the dump resistor; CIS180: Current through the fast closing short circuit path; CIS280: Current through the slow closing short circuit path

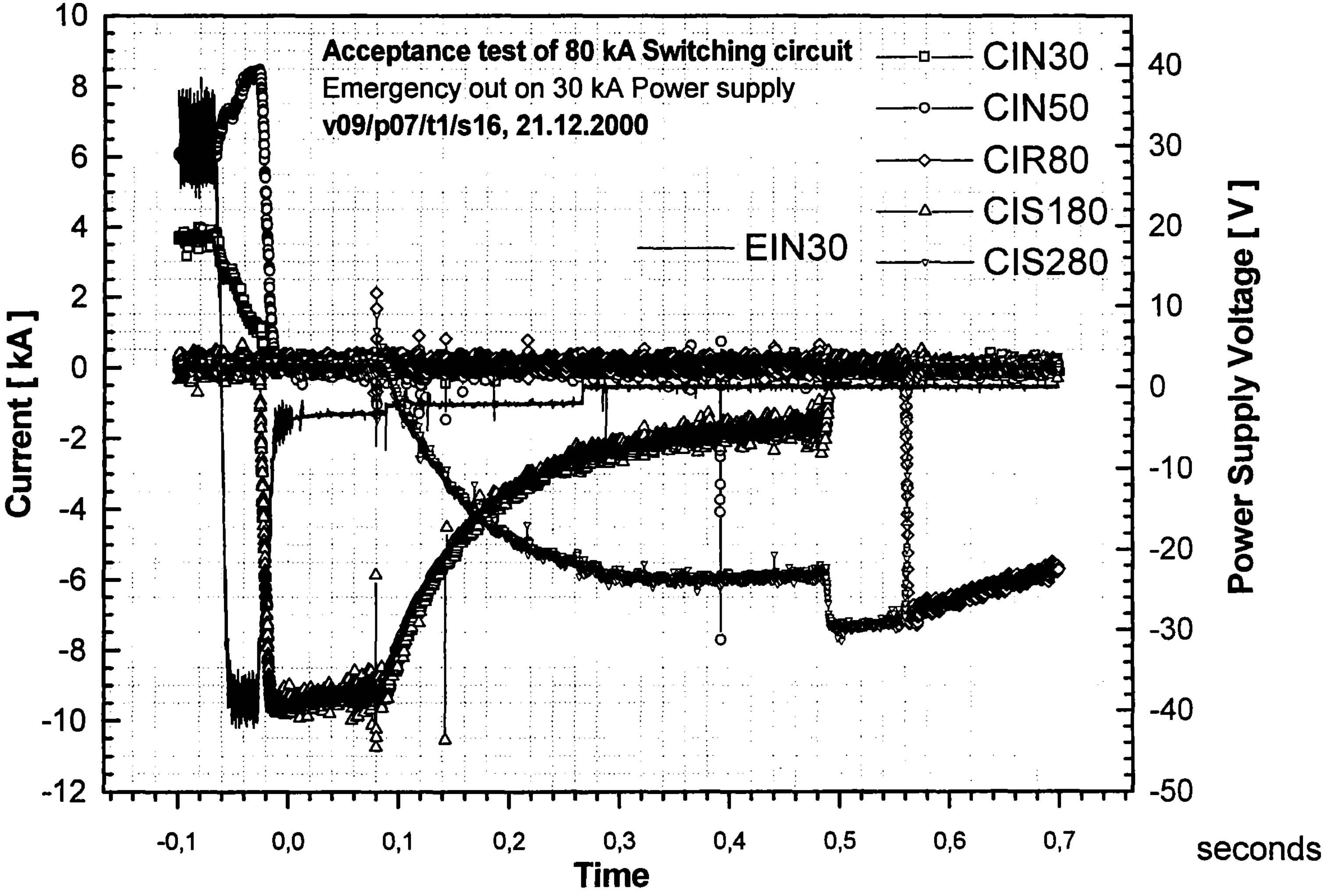


Fig. 3.4.5-6: Voltage and current traces during a safety discharge using the 80 kA power supply and the 80 kA dump circuit released by switch off of the 30 kA power supply. (EIN30: Voltage of the 80 kA power supply; CIN30: Current of the 30 kA power supply; CIN50: Current of the 50 kA power supply; CIR80: Current through the dump resistor; CIS180: Current through the fast closing short circuit path; CIS280: Current through the slow closing short circuit path

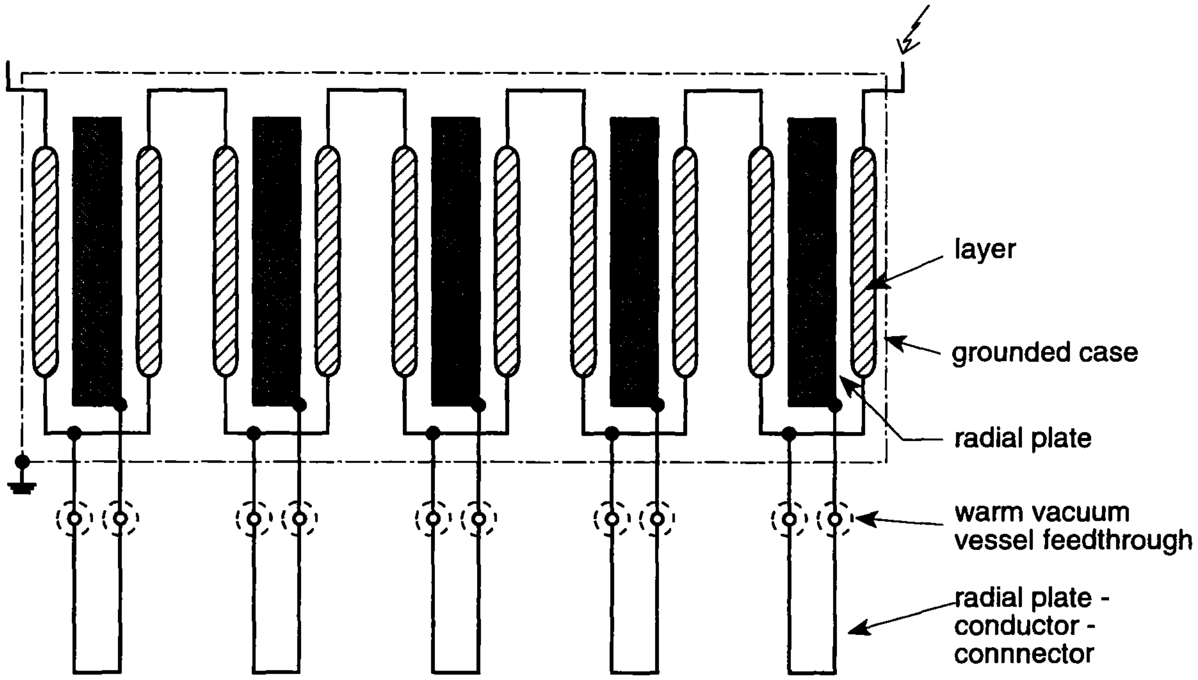


Fig. 3.4.6.1-1: Arrangement of the ITER TFMC for partial discharge measurement on ground insulation

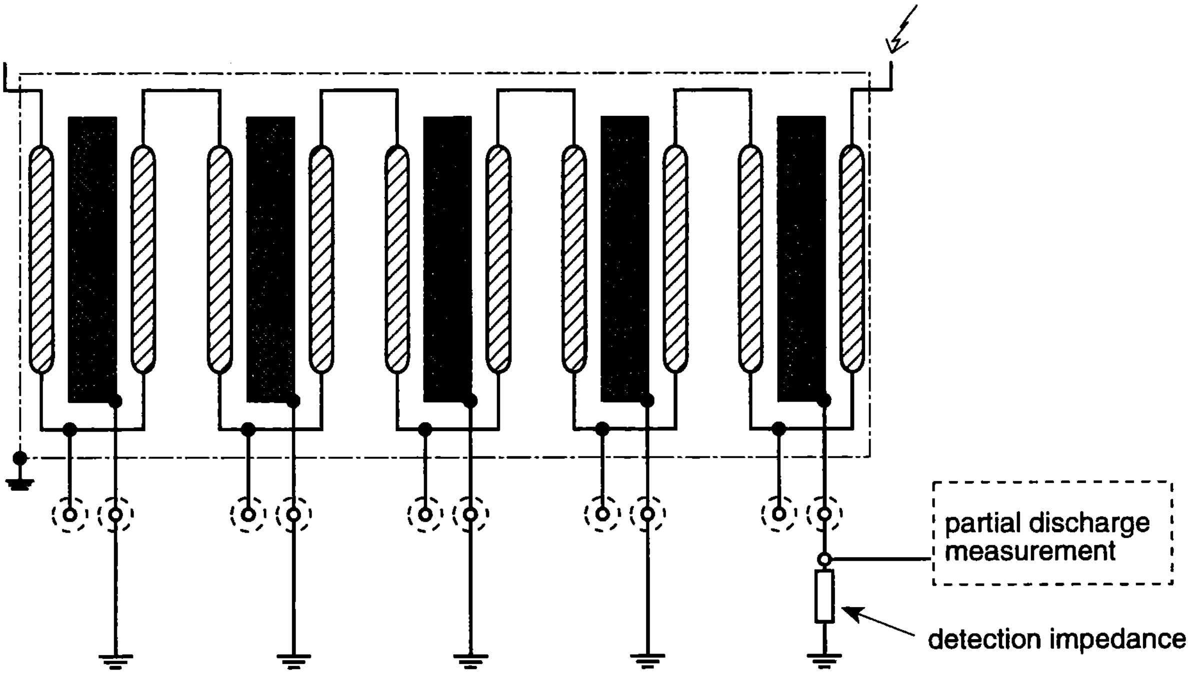


Fig. 3.4.6.2-1: Arrangement of the ITER TFMC for partial discharge measurement on conductor insulation

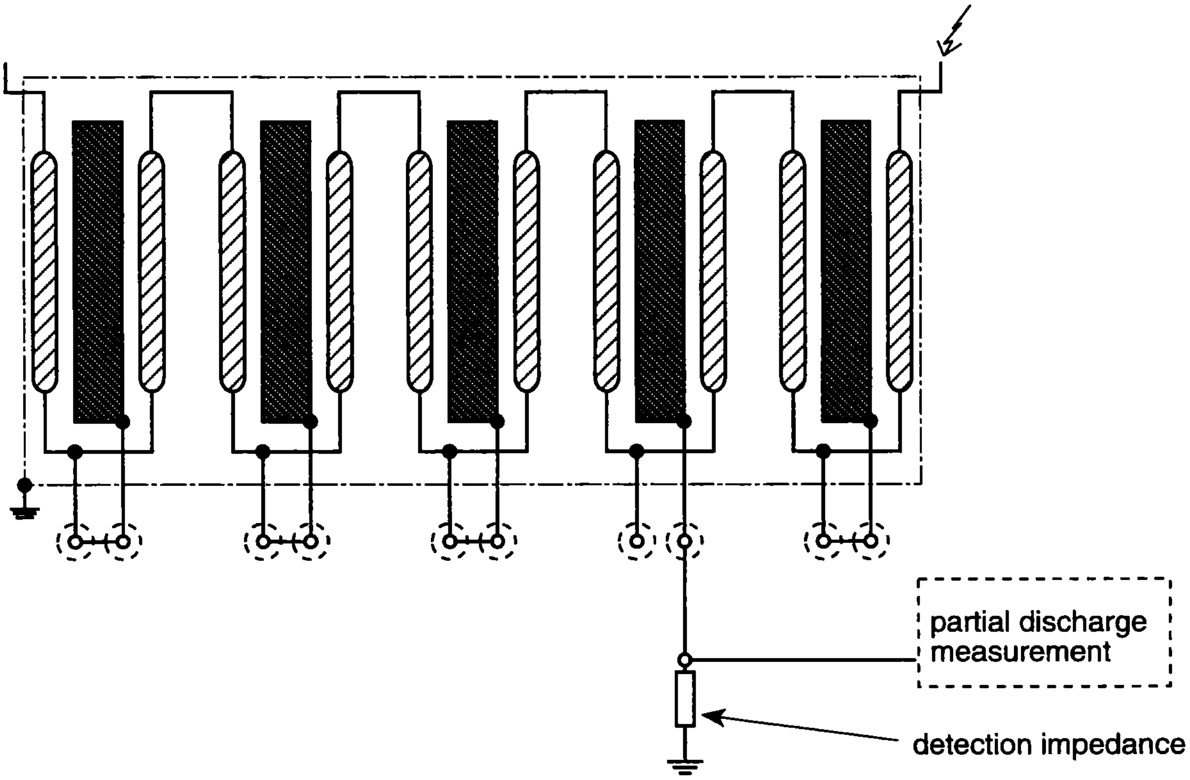


Fig. 3.4.6.3-1: Arrangement of the ITER TFMC for partial discharge measurement on insulation between radial plates

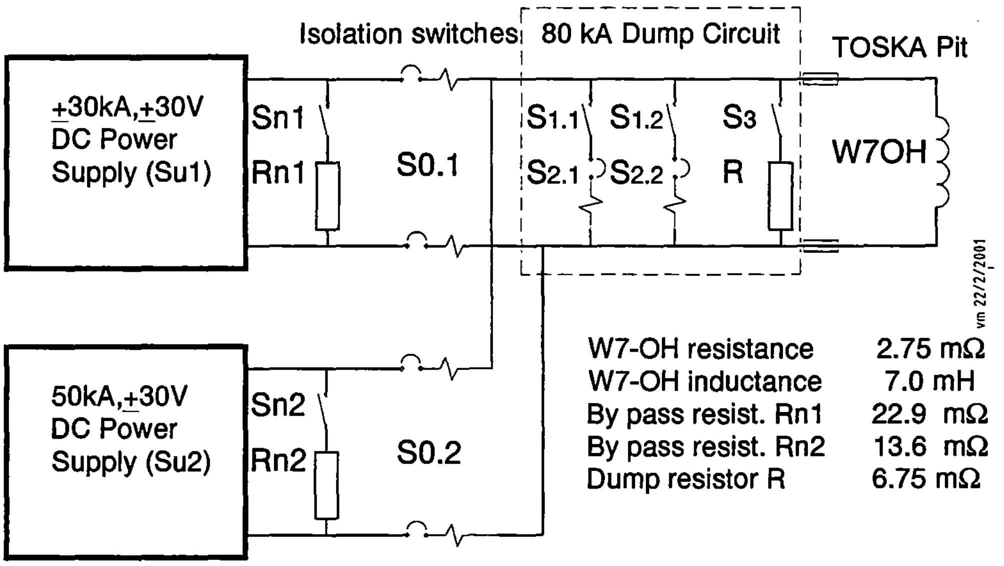


Figure 3.4.7-1 Circuit diagram of the 80 kA Power System with W7-OH coil.

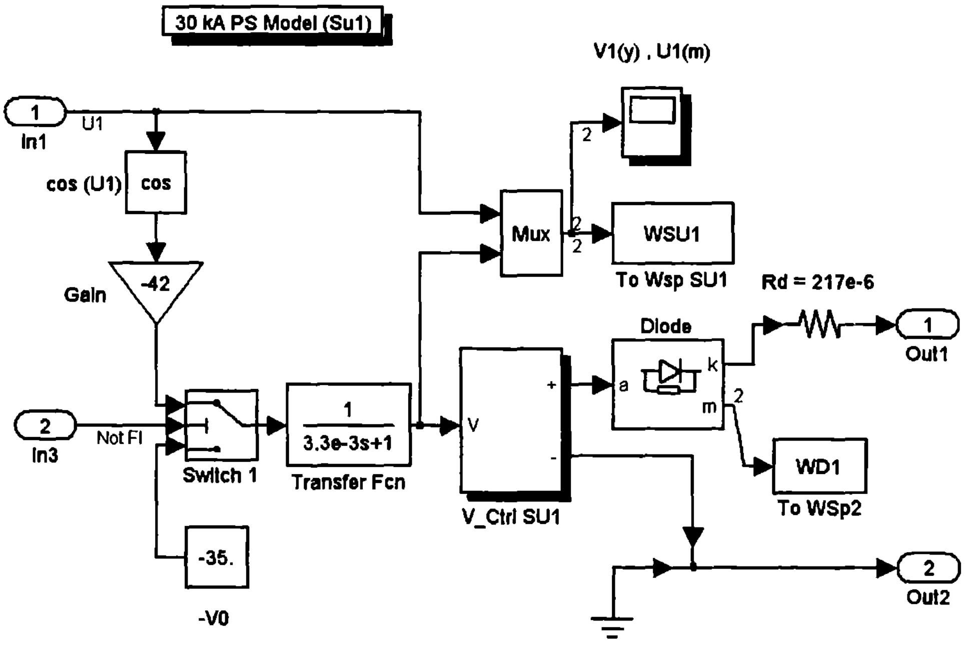
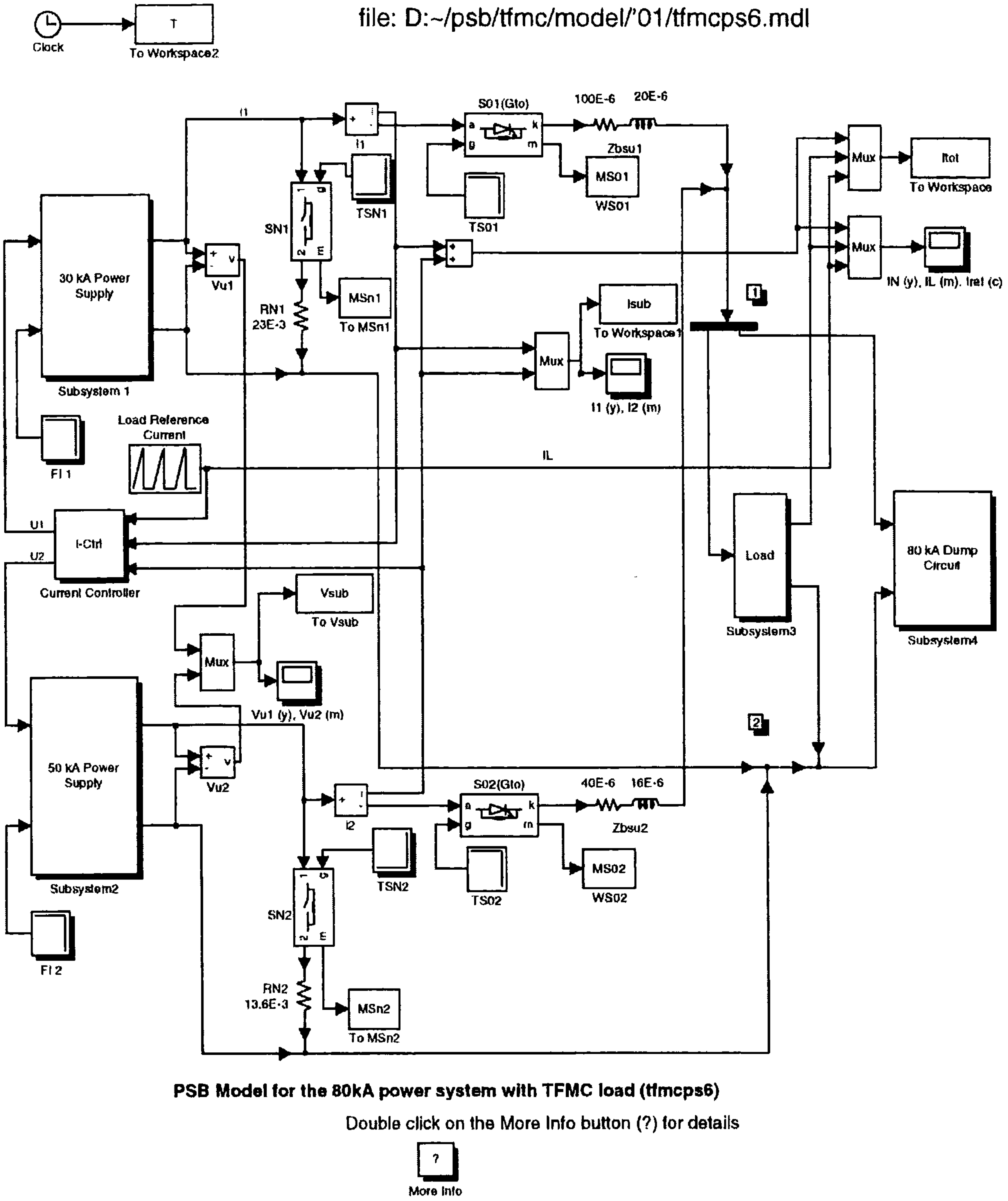


Figure 3.4.7-2 DC Equivalent model of the 30 kA power supply



file: D:~/psb/tfmc/model/'01/tfmcps6.mdl

PSB Model for the 80kA power system with TFMC load (tfmcps6)

Double click on the More Info button (?) for details

Figure 3.4.7-3 PSB model for the 80 kA power system (overview)

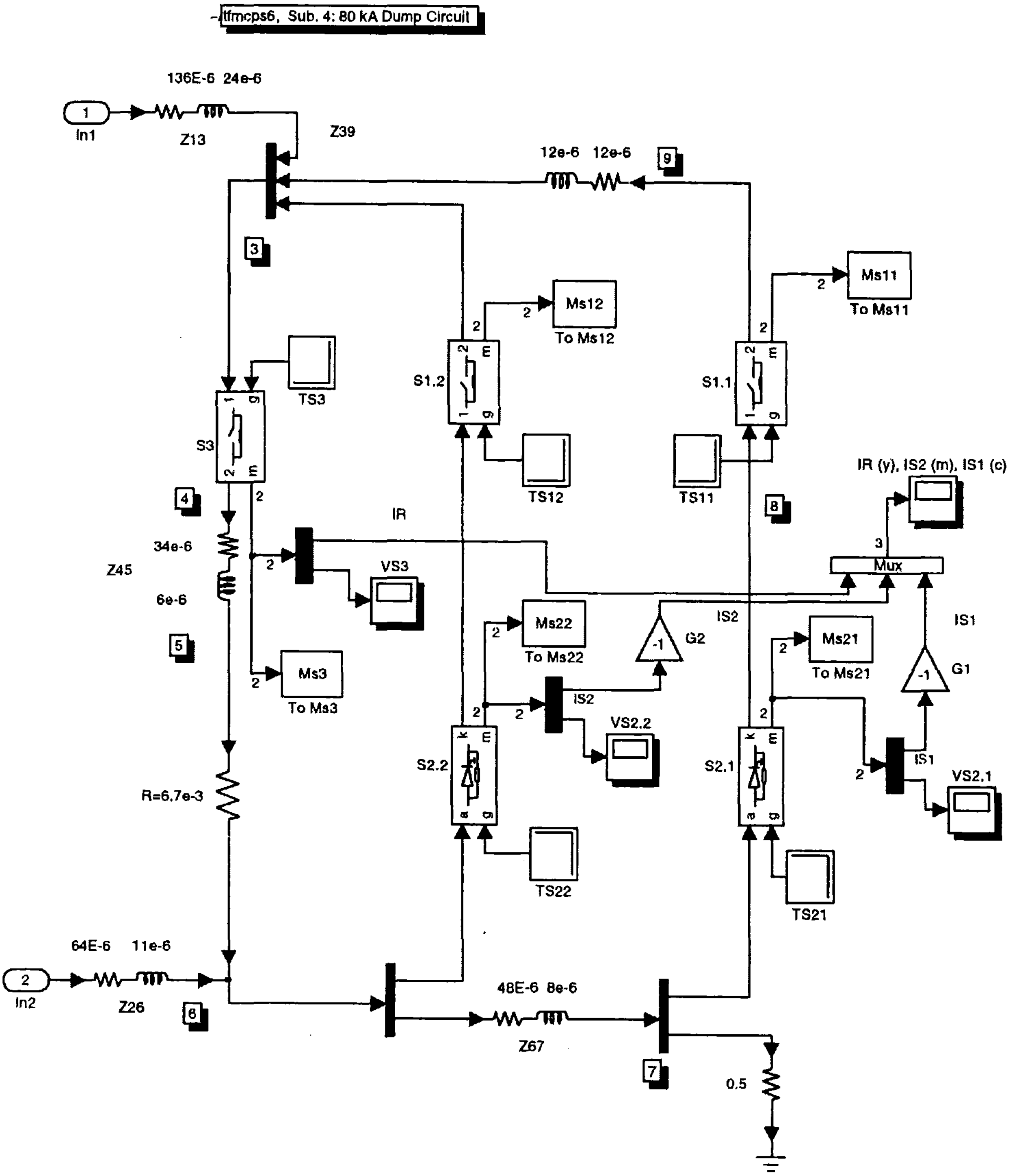


Figure 3.4.7-4 PSB model for the 80 kA dump circuit

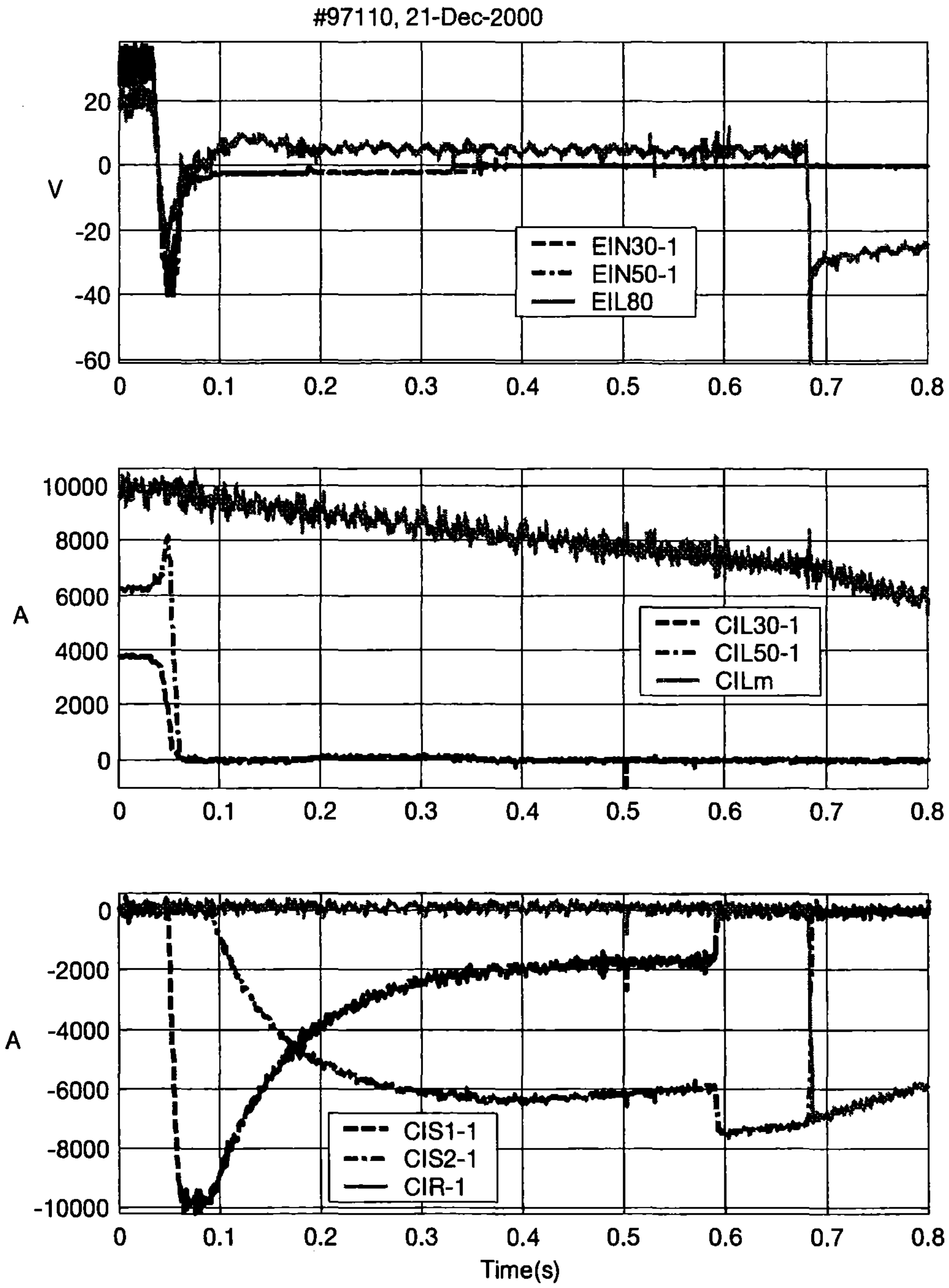


Figure 3.4.7-5 W7-OH Safety Discharge at 10 kA triggered manually from the 80 kA DPC

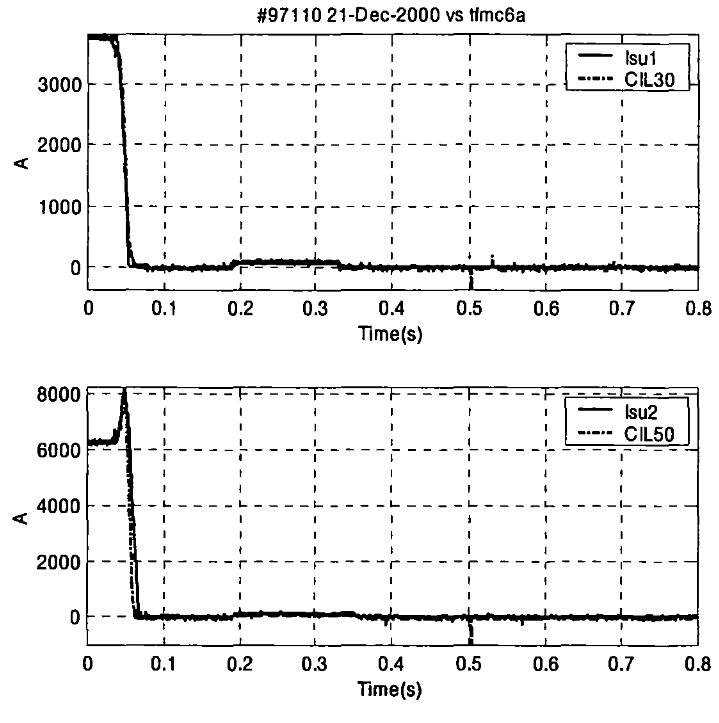


Figure 3.4.7-6: Measured 30 and 50 kA power supply currents versus model

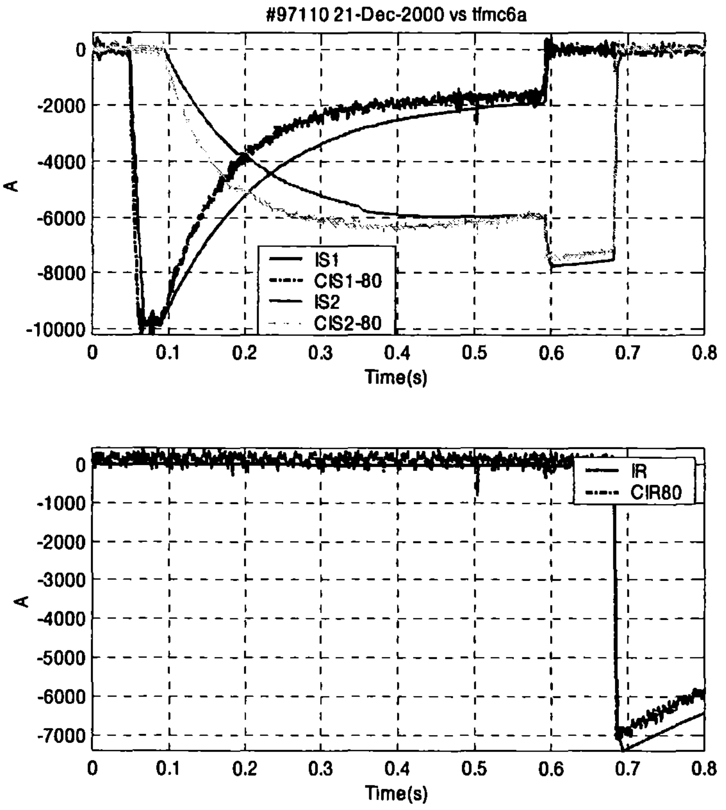


Figure 3.4.7-7: Measured crowbar and dump resistor currents versus model

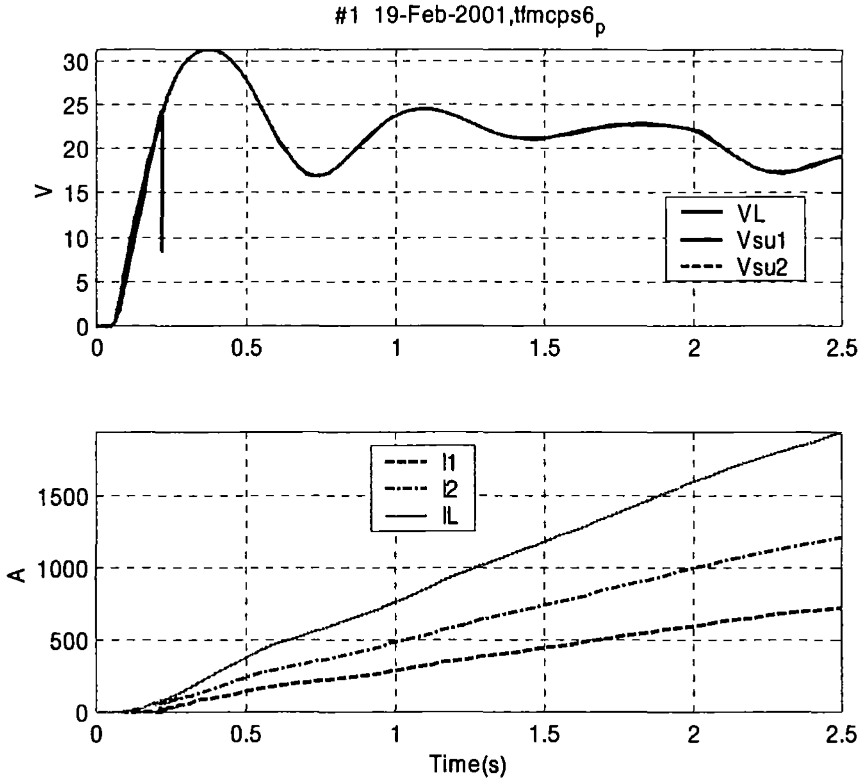


Figure 3.4.7-8: Voltage and current transients at startup (di/dt = 821 A/s)

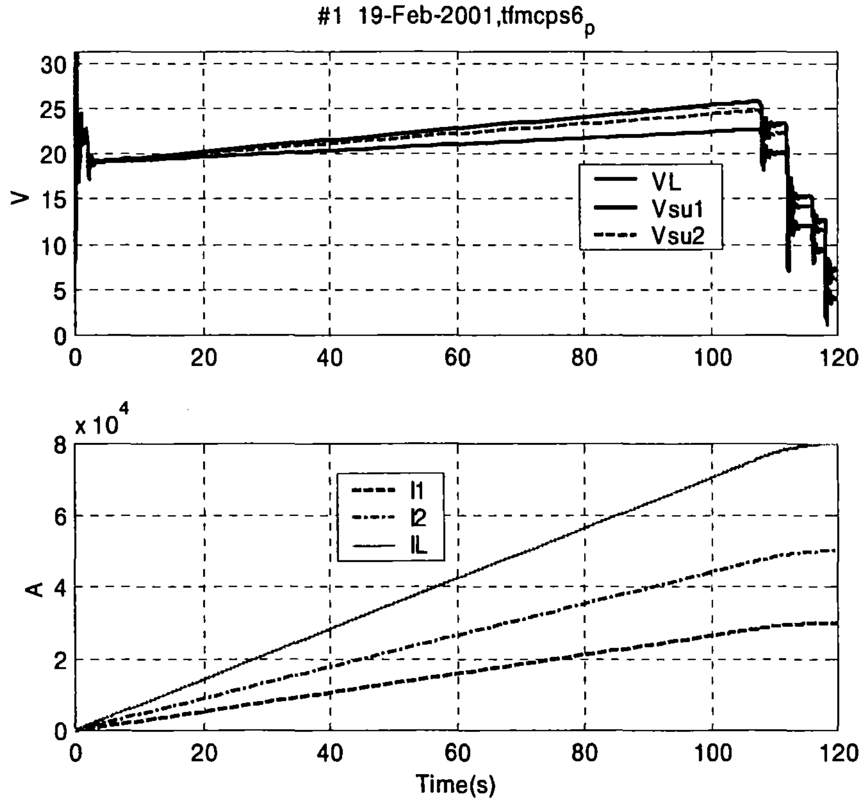


Figure 3.4.7-9: Voltage and current transients during ramp up to 80 kA

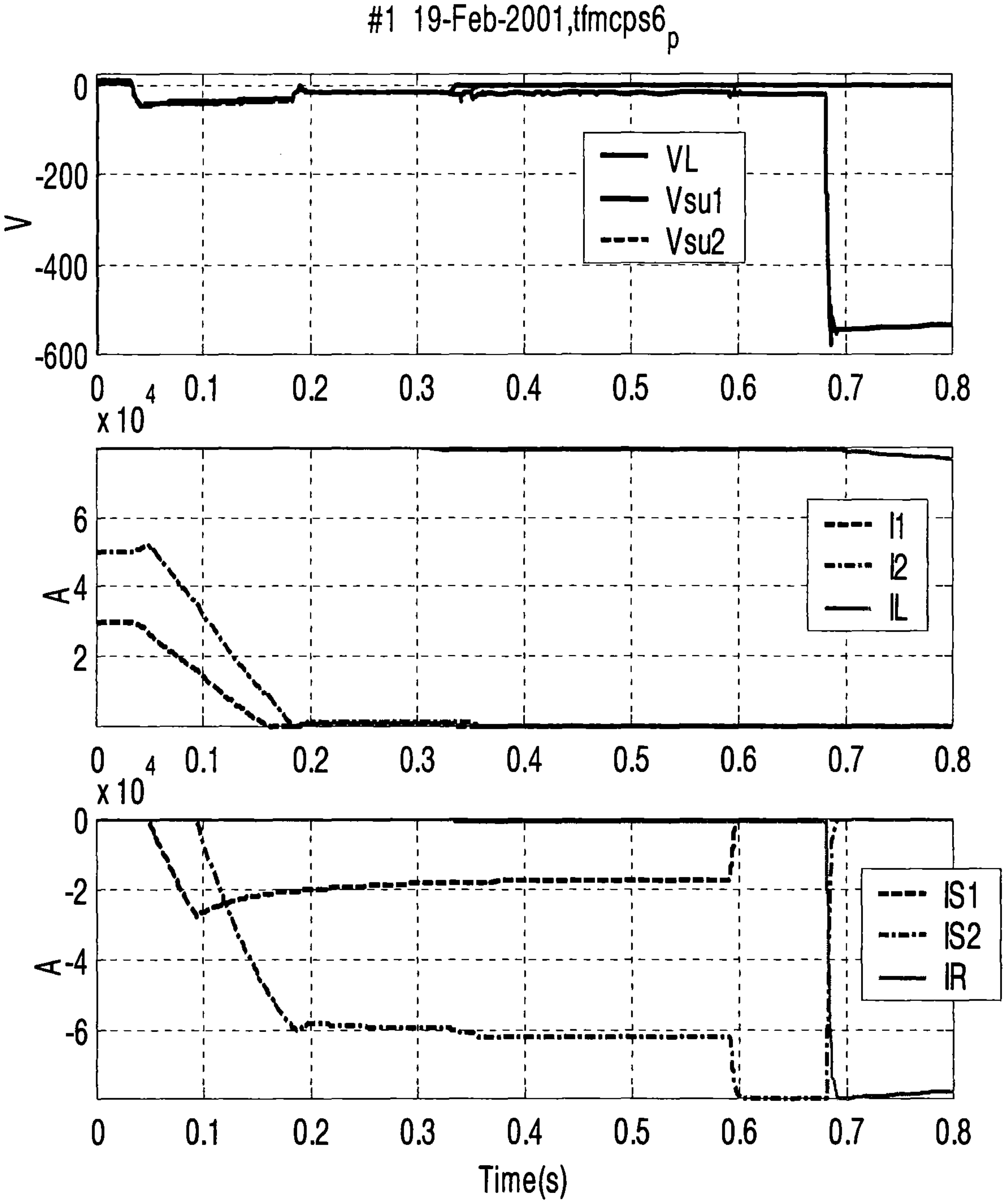


Figure 3.4.7-10 TFMC simulated safety discharge at 80 kA. Case 1: fast and slow crowbar activated.

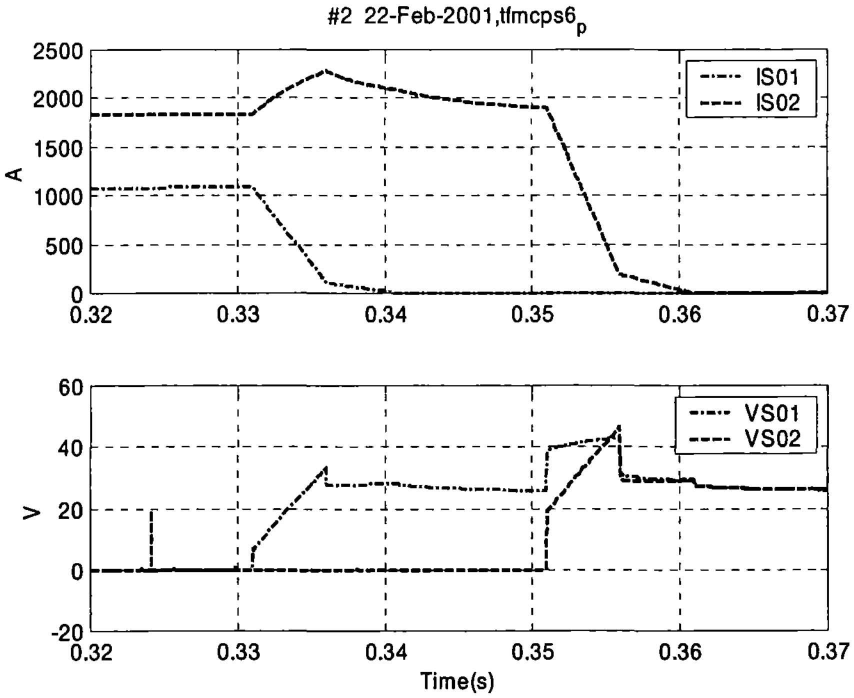


Figure 3.4.7-11 TFMC simulated safety discharge at 80 kA: isolation switches voltages and currents for case 1 (fast and slow crowbar).

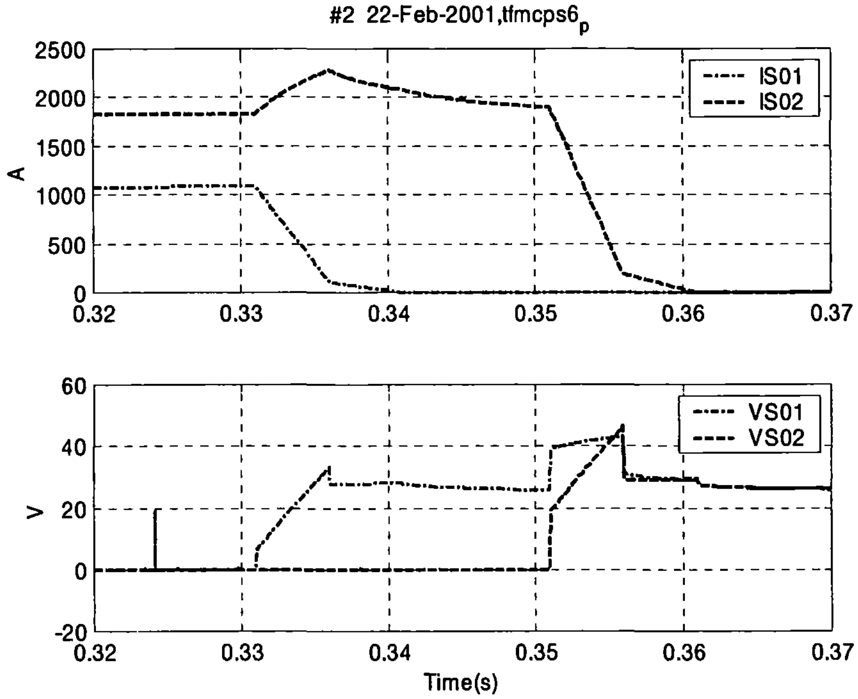


Figure 3.4.7-12 TFMC simulated safety discharge at 80 kA: isolation switches voltages and currents for case 2 (fast crowbar only).

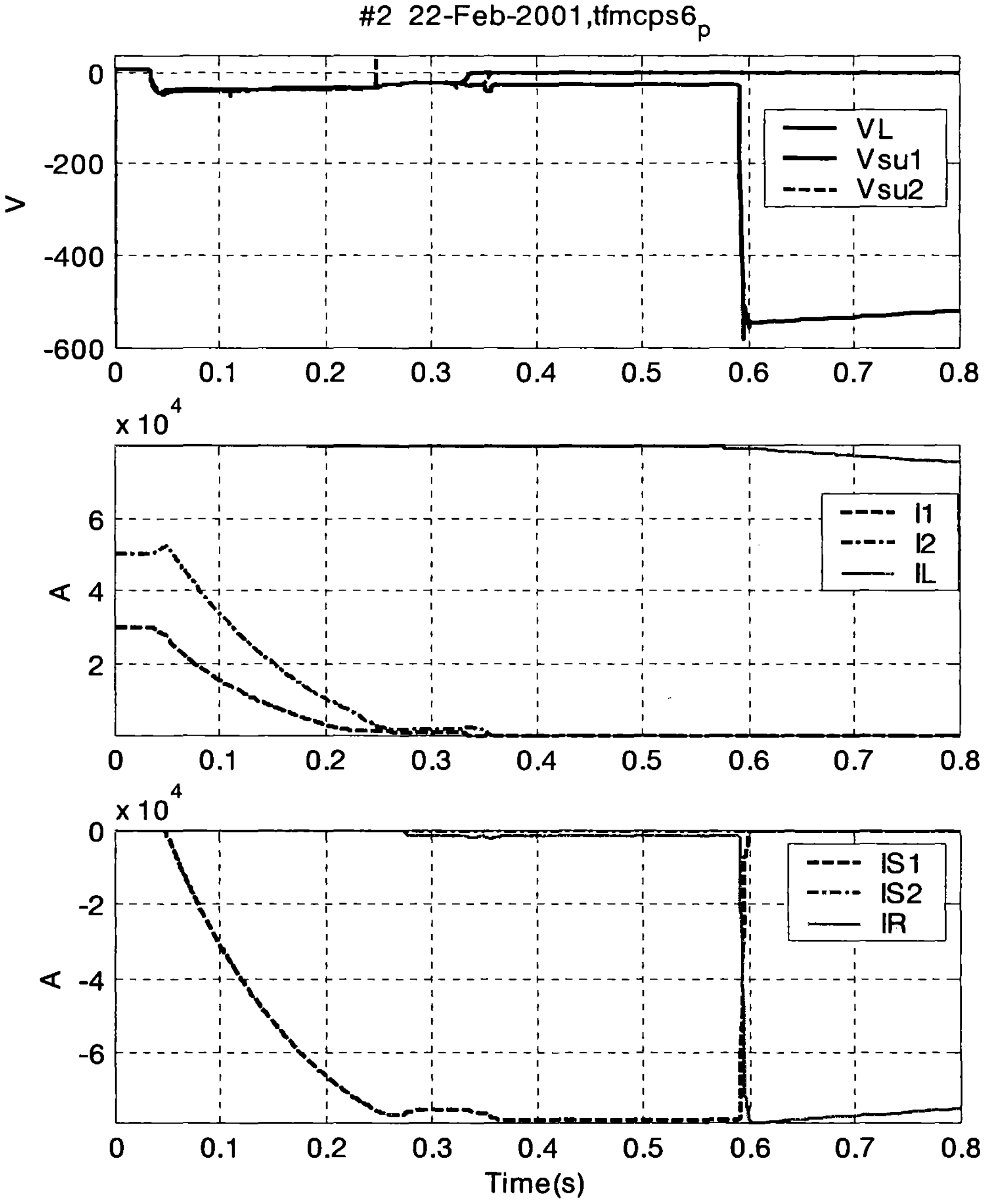


Figure 3.4.7-13 TFMC simulated safety discharge at 80 kA. Case 2: only fast crowbar activated.

3.5 Measuring, control and data acquisition

3.5.1 General description, overview [3.5.1-1]

Every component of the TOSKA facility is equipped with an adequate instrumentation for measuring and control in order to operate the facility in standby mode without attendance. This part of the TOSKA facility was completely modernized after the completion of the POLO Project 1995.

While the measuring and control of the power supplies has to be considered as a „black box", those ones of the cryotechnique and of the electrical safety discharge circuits as well as their interaction have to be optimized during operation. This work was a collaboration with industry, experts from the HPE/FZK and the ITP.

The sensors of the cryogenic system are the same types used for the superconducting coil or vice versa. Most of them have no linear characteristic over the whole temperature range from 1.8 K to 300 K. The digitized measuring values have to be converted by the sensor characteristic in the dedicated computer system to engineering units. Some of the thermohydraulic quantities, e.g., the mass flow of helium gas, heating power, have to be calculated from other measured values (differential pressure, pressure, temperature). Some of the sensors (voltage taps, temperature) are at high voltage potential and have to be linked to the common signal conditioning by special developed isolation amplifier. The data of the sensors described are fed into the system every 5 s by computers (rtVAX 300 – 1, 2, 3), pogrammable logic controllers (PLC) and scanners (Fig. 3.5.1-1).

The facility is controlled by PLC's which communicate with the master system. Operators can follow the status of the facility on work stations (e.g., VAX-Station 4090) and can handle the facility by display and mouse click. The facility is handled by an emergency unit in case of a breakdown of the computer system or the local area network.

The cryogenic system of the TOSKA facility communicates with the process system TELEPERM of the 2 kW refrigerator. The PLC of the safety discharge circuits and the power supplies is only in operation during magnet testing. The transient data acquisition is only triggered by certain events e.g., a safety discharge, heater pulses etc. For special measurements, certain sensors have to be summarized in a group which can be triggered to a certain event independently from the safety discharge. All measured data are stored in the data base ORACLE in engineering units. They are available for evaluation by PCs.

The TOSKA facility is operated in two shifts during an experiment. Overnight and on weekends, the facility is in unattended standby mode.

The measuring and control system as well as the data acquisition system was successfully tested in its basic components at the 1.8 K test of the LCT coil [3.5.1-2] and the test of the W 7-X prototype coil [3.5.1-3]. It has to be rearranged each time for the special requirements of the test objects.

3.5.2 Control system

The control engineering of the cryogenic system is realized by means of two PLC's (S5-135, Siemens) and conventional hardware controller (DR22, Siemens) (Fig. 3.5.1-1, system 2). One PLC handles the infrastructure system (cryogenic supply, vacuum, etc.), the other one controls the test magnets (LCT-coil and TFMC). The number of PLC channels are given in Table 3.5.2-1. The number of transducers and controllers for the TFMC are summarized in Table 3.5.2.2-2. The usual operation is done by a visualization system (section 3.5.6). This system is connected by means of a third PLC (data concentrator). The alarm handling is executed on the level of the individual PLC. In case of failure of components like the data concentrator, the visualization system or the bus connection, the system can still be operated at reduced performance by an emergency operation panel. The fail-safe conditions are realized by hardwired pressure switches. The basic layout is shown in Fig. 3.5.2-1 and Fig 3.5.2-2.

Table 3.5.2-1: Number of PLC-channels

No. of channels	*Infrastructure PLC*	*Test PLC- LCT*	*Test PLC- TFMC*
Digital - Input	192	64	128
Digital - Output	160	96	128
Analog - Input	96	64	88
Analog - Output	24	16	32

The scan rate of each individual PLC is lower then 100 ms. Therefore the response time in case of alarms is in the range of 200ms.

Table 3.5.2-2: Number of transducer and controller for TFMC

Transducer, controller	*Number foreseen for TFMC*
Differential pressure	20
Pressure	20
Mass flow	2
Controller	15

The number of temperature measurements is described in section 3.5.4.

3.5.3 Quench detection system

Each pancake is equipped with his own quench detector. To get redundancy, each detector is doubled (Fig. 3.5.3-1). The detector watches the resistive voltage drop of the pancake by voltage taps applied as co-wound tapes. The analytic circuit contents clipper, RC-low pass filter, comparator and output stage with galvanic isolation. Output is a (normally closed) relay contact. Additionally the input circuit sends a DC current (0.8 µA to 0.8 mA, depending on the selected threshold) through the voltage tap to indicate a wire break [3.5.3-1]. The whole device is made in fail save performance. A quench, a wire break or a failure of one component of the electronic of the quench detector initiates a dump. The threshold and time constant are selected in fixed steps.

Threshold steps: 1-2-5-10-20-50-100-200-500-1000 mV.

Time constant (delay) steps: 0.01-0.02-0.05-0.1-0.02-0.05-1-2-5-10 S

Isolation voltage: 20 kV,

Supply voltage: 230 V AC.

3.5.4 Slow scanning system

The slow scanning system is divided in different subsystems in accordance to the specific requirements of signal conditioning and characteristics of the sensors [3.5.1.-1]. Due to the hardware components, each subsystem has a different operation software. The data transfer to the on line data base is done by inter-process communication (IPC).

3.5.4.1 CAMAC subsystem

All temperature sensors as platinum resistors, carbon resistors, carbonglas resistors, Cernox resistors [3.5.4.1-1] and TVO resistors [3.5.4.1-2] are sampled at three CAMAC Crates. An intelligent controller sends the raw data into the archives and performs the calculation of the engineering units and transfer to the data base. Depending of the sensor types, the signals are routed to the specific crate. All sensors belonging to the facility and LCT coil are routed to CAMAC Crate 1 and 2. The main part of the TFMC temperature sensors are associated in CAMAC crate 3. In order to keep the heating power less than 1 µW, the current supplies of the sensors are adjusted by computer control. On line data are available every 2 seconds. The present design of the CAMAC system is able to handle 360 temperature sensors: 120 channels platinum resistors, 105 channels carbon resistors, 45 channels carbonglas resistors and 90 channels TVO/CERNOX resistors.

For diagnostic and control of the facility and the LCT coil, 80 channels of Pt resistors, 100 channels of carbon resistors and 30 channels of carbonglas resistors are already occupied (total 210).

150 channels are still available. The scanning rate is 0.5 Hz.

Required for testing the TFMC, 75 channels are needed, distributed to 55 TVO/CERNOX sensors and 20 Pt sensors [3.5.4.1-3].

3.5.4.2 Hottinger subsystem

All strain gauge based sensors as well as DC-signals are assigned to three Hottinger devices with 60 channels each, which are scanned in parallel. Out of the 180 channels, 70 channels are used for sensors applied at the LCT coil. Sampling of the raw data and calculation of the engineering units are done by a personal computer. On line data are available every 5 seconds.

110 channels are still available. The scanning rate 0.2 Hz

Planned for TFMC test [3.5.4.1-3]:.86 channel; Requested : 95

distributed to strain gauge type (half bridge)	34 sensors
strain gauge type (rosettes)	11 sensors
DC voltage sensors	28 channel

3.5.4.3 Programmable logical controller (PLC):

All sensors which are related to cryogenic control as pressure, differential pressure, level indicator, valve control and positioner, heater etc. are assigned to different PLCs. Control and protection of the test facility as well as sampling of the raw data and transfer to engineering units are realized with this subsystem. This is already described in detail in section 3.5.2

3.5.5 Fast scanning system

For acquiring of transient events like safety discharge, stability measurements, representative sensors are allocated to the transient recorder. The recorder are placed in three CAMAC crates with 16 modules and four channels each. Triggering of transient events can be done independently for each crate. The sampling rate and storage depth must be set in advance. The sampling frequency can be set in discrete steps as

1, 10, 100 Hz, 1, 10, 50, 100, 500, 1000 kHz .

Three blocks of 64 channels each (192 channels in total) with 64 k storage depth.

Sampling frequency:	1 Hz up to 1 MHz
Trigger :	Each block independently

3.5.6 High voltage signal conditioning

Most of the transient signals are at high voltage potential. Therefore, special signal routings are necessary to the isolated amplifiers. The signal conditioning of such signals requires particular attention. The LCT coil related high voltage signal conditioning of the compensated voltages remained as it was during the domestic test at 1984 [3.5.6-1].

The present signal routing and signal conditioning for the TFMC test cover all requirements about diagnostic and protection. The voltage taps connected to the TFMC winding and their patching are presented in Fig. 3.5.6-1 and Fig. 3.5.6-2. Each high voltage instrumentation cable at the potential of the inner joints (high field joint) or of the shear disks is routed to a HV patching box in the vacuum vessel area (Fig. 3.5.6-1). In this type of patch box the connection between shear disk and inner joint potential is performed across a resistor or a fuse for normal current operation (Fig. 3.4.4.1-4). This connection has to be separated for partial discharge measurements as described in section 3.4.6. From these patch boxes, the cables are routed to the HV cabin. In a second type of HV patch boxes the cables are patched to the individual isolation amplifiers for each channel (Fig. 3.5.4-2). Voltage taps which are used for measuring the voltage drop across pancakes run across a fuse boxes to avoid damage to the instrumentation cables in case of a short at the amplifier side.

For signal conditioning the following components are needed:

Patch panel :	16 boxes
High voltage fuse :	6 boxes
Isolated amplifier :	57 modules
Quench detector	24 modules

3.5.7 Fast scanning system (transient data acquisition)

For acquiring of transient events like safety discharge, stability measurements, representative sensors are allocated to the transient recorder (Fig. 3.5.1-1, system 4). The recorder are placed in three CAMAC crates with 16 modules and four channels each. Triggering of transient events can be done independently for each crate. The sampling rate and storage depth must be set in advance.

Three blocks of 64 channels each	64 k storage depth
Sampling frequency	1 Hz up to 1 MHz
Trigger:	Each block independently

3.5.8 Operation systems and software used [3.5.1-1]

VXL was selected as control system running under Open VMS on VAX stations as well as on Alpha platforms.

RTDB, VXL's Real-Time Data Base using ORACLE RdB, is a database management system especially developed for data retrieval in a real-time environment. The tables of ORACLE RTDB, VXL's Real-Time Database using RdB contain all the information needed to describe graphical objects on a screen or sub window and are accessible by the application programmer. Using VXL ACCESS, a library of database access routines, a programmer can write custom application programs to run concurrently and to exchange data with subsystems. The data flow into and out of RTDB is shown in Fig. 3.5.8-1. Except for the transient recorded data all subsystems data are stored in RTDB from which they are accessed and periodically recorded.

VXL provides utilities to set up the data blocks and data types used in the PLCs data concentrator. About 22 data blocks are defined, each holding 256 16-bit unsigned integer words for digital and analogous input-output-data. The above mentioned data blocks are dedicated in VXL to an external data source. A set of the incoming data is taken to execute calculations, visualization, alarm and event handling.

VXL has integrated the powerful graphical editor DATA VIEWS which allows to design the users interface to the process and windows to display and monitor process data. To control and visualize all the operations in the TOSKA facility, about 40 high resolution (1280 X 1024) windows and 25 sub windows are available to the operator.

The engineering unit data collected by the VXL real time database (RTDB) are recorded periodically into the relational ORACLE database by the archives server. After a session, recorded data may be concentrated to save hard disk space by requesting to delete any recorded data of a user-specified time period except, e.g., one value per hour.

For visualization of recorded data, the scientific data analysis software package ORIGIN is coupled to the graphical database user interface

ORACLE Forms via DDE, a standardized interface to transfer data between MS Windows applications.

To reduce transmission time, the user may choose a time interval and specify to see, e.g., only one value per 20 minutes for a quick look at the data.

In addition, to periodically recording physical data, transient data are also stored in the ORACLE database. For visualization, similar tools are available to the one described above.

3.5.9 Impact of magnetic fringe fields

One goal of the second test of the TOSKA facility with the LCT coil was to investigate the impact of magnetic fringe fields on installed electrical equipment as the control units for the 30 kA power supply, operation of the POLO dump circuit, programmable logic controllers (PLC) and intelligent controllers up to the highest possible field level [3.5.9-1],[3.5.9-2].

The last test showed that compact arrangement of different components in the experimental area are influenced by magnetic fringe fields. Measurements of the fringe fields at certain positions allow scaling to future tests (Tab. 5.9-1). The operation of the LCT coil at 19 kA corresponds to 65 % of the Ampere turns of the TF model coil configuration. Fig. 3.5.9-1 shows the fringe field levels in the basement where the 30 kA power supply and the POLO switching circuit are located. Fig. 3.5.9-2 shows the fringe field level in the control room.

The operation of the POLO switching circuit and the 30 kA power supply which will be later used also in the TFMC test were tested in relevant fringe field levels with a resistive coil. Safety and high voltage discharge mode of the POLO circuit were tested up to 3.3 MA turn in the LCT coil and worked well. The fringe field of 1.0 MA turn is required for transient TFMC testing.

In getting some experience for the 80 kA TFMC dump circuit the safety discharge mode of the POLO switching circuit was investigated up to the maximum background field generated by 11.2 MA turns. It was found that the control unit of the POLO dump circuit showed disturbances at about 7.6 MA turns which corresponds to local field levels of about 3 mT in the control unit. It was found out that the malfunction of Reed relays blocked the control loops. After overcoming the problem by changing the orientation of the relays the control unit of the dump circuit worked up to 11.2 MA turns LCT coil excitation. At these Ampere turns the background field level at the DC arc chute breaker was about 25 mT. No impact was observed on the breaker operation.

Another problem arose at the power supply current transformer (Type Foeldi, Switzerland, ± 30 kA) which showed saturation effects at about 10 MA turns LCT coil excitation corresponding to a field level of about 5 mT. An iron plate screening brought a screening of about 0.5 so that the power supply and dump circuit worked well up to the maximum possible 11.2 MA turns.

Increasing current levels at the test of the W 7-X prototype coil led again to saturation effects in the current transformer core. Some experiments showed that the saturation effect cannot be mastered by screening because the superimposed field levels (busbar field + fringing field) are too high. Presently it is investigated to perform the current measurement by a shunt resistor or a LEM current transformer which is less sensitive against superimposed magnetic fields. In both cases the accuracy of the current measurement is reduced from about 10^{-4} to 10^{-3}. This is acceptable compared to the operation disturbance of the electrical supply system.

A PLC was tested with a special test routine. The main parts of the PLC (CPU, CP, I/O-components) where tested in a stray field up to 22 mT. No malfunction was observed up to 17 mT. The conditions during operation will be in the range of 1.5 mT to 1.8 mT.

In case of testing the TFMC, this level will increase nearly by a factor of two.

A centrifugal pump for He I/II operation (dm/dt = 60 g/s at 200 rev/s) was tested during ramp up, flat top at 19 kA and ramp down. No impact on mass flow rate was observed. The fringe field at the pump location was in the range of 6 mT.

Summarizing the gained experience, the most critical items are air core driven relays and elements with soft magnetic cores. The impact is strongly dependent on the magnetic field direction at the location of the elements.

The following guide lines can be given:

Air core driven relays have to be avoided in control circuits to exposed magnetic fringe fields.

Control units have to be located in areas with fringe field levels < 2 mT.

Screening by iron shields is applicable for units with locations already fixed and not changeable. The effectiveness of the screening have to be checked every at the real operation field level.

Table 3.5.9-1: Test arrangements in the TOSKA vacuum vessel
The table allows a scaling of the magnetic fringe fields in the experimental area of TOSKA for the different test configurations. The fringe field is in a first approximation direct proportional to the number of Ampere turns.
Coil axes perpendicular to vacuum vessel axes: perp.
Coil axes parallel to vacuum vessel axes: par.

Coil Configuration	**Conductor Current [kA]**	**Ampère Turns [MPa]**	**Position**
LCT	10.0	5.88	perp.
LCT	19.0	11.2	perp.
POLO	15.0	0.84	par.
POLO	22.5	1.25	par.
LCT + W7-X	LCT (14) + W7-X (18.7)	11.0	perp.
LCT + ITER TF	LCT (16) + ITER TF (80.0)	17.2	perp.
ITER TF	80	3.2	perp.
ITER TF	25	1.0	perp.

3.5.10. References

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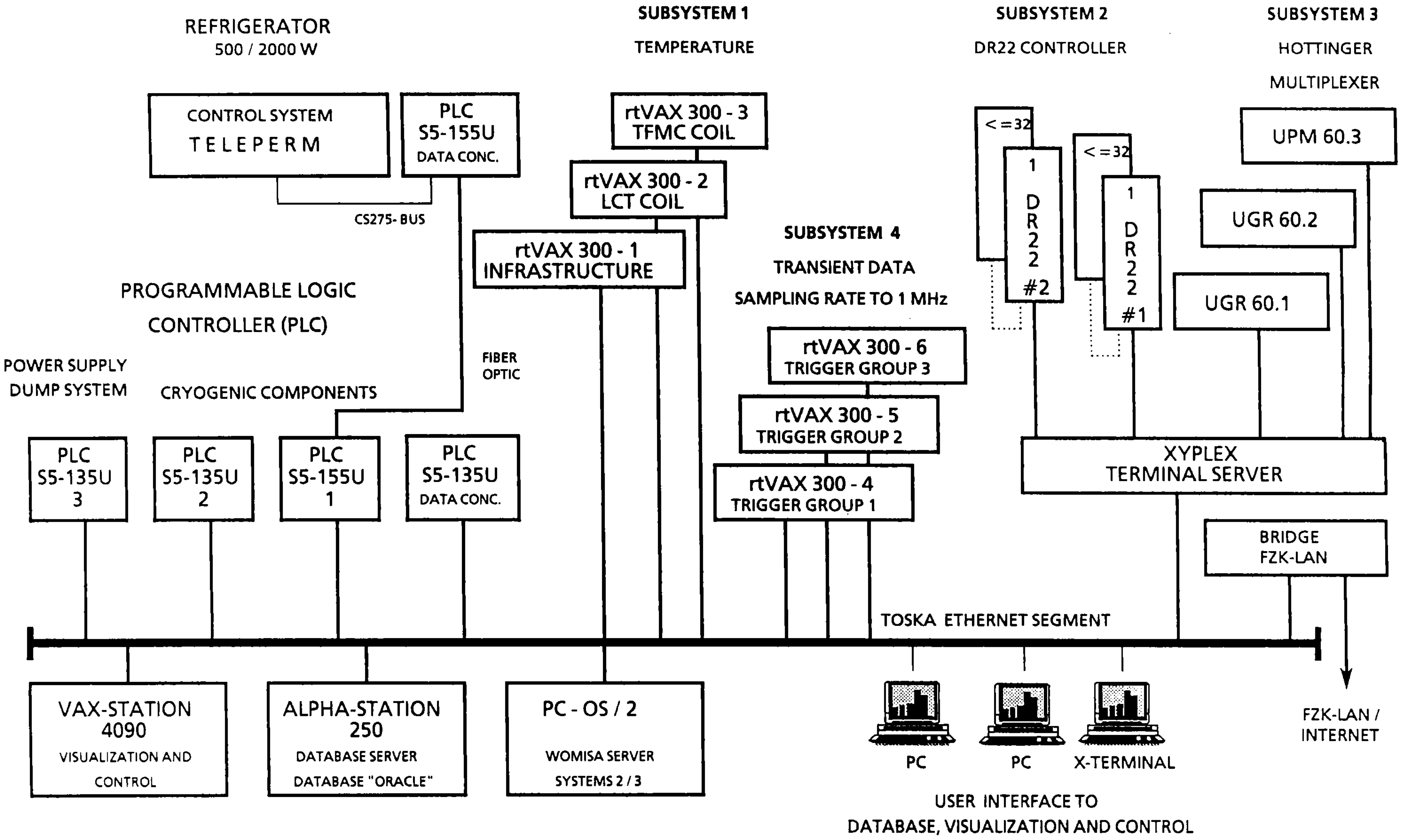


Fig. 3.5.1-1: The data acquisition system of the TOSKA facility. All components of the system communicate across the TOSKA Ethernet segment.

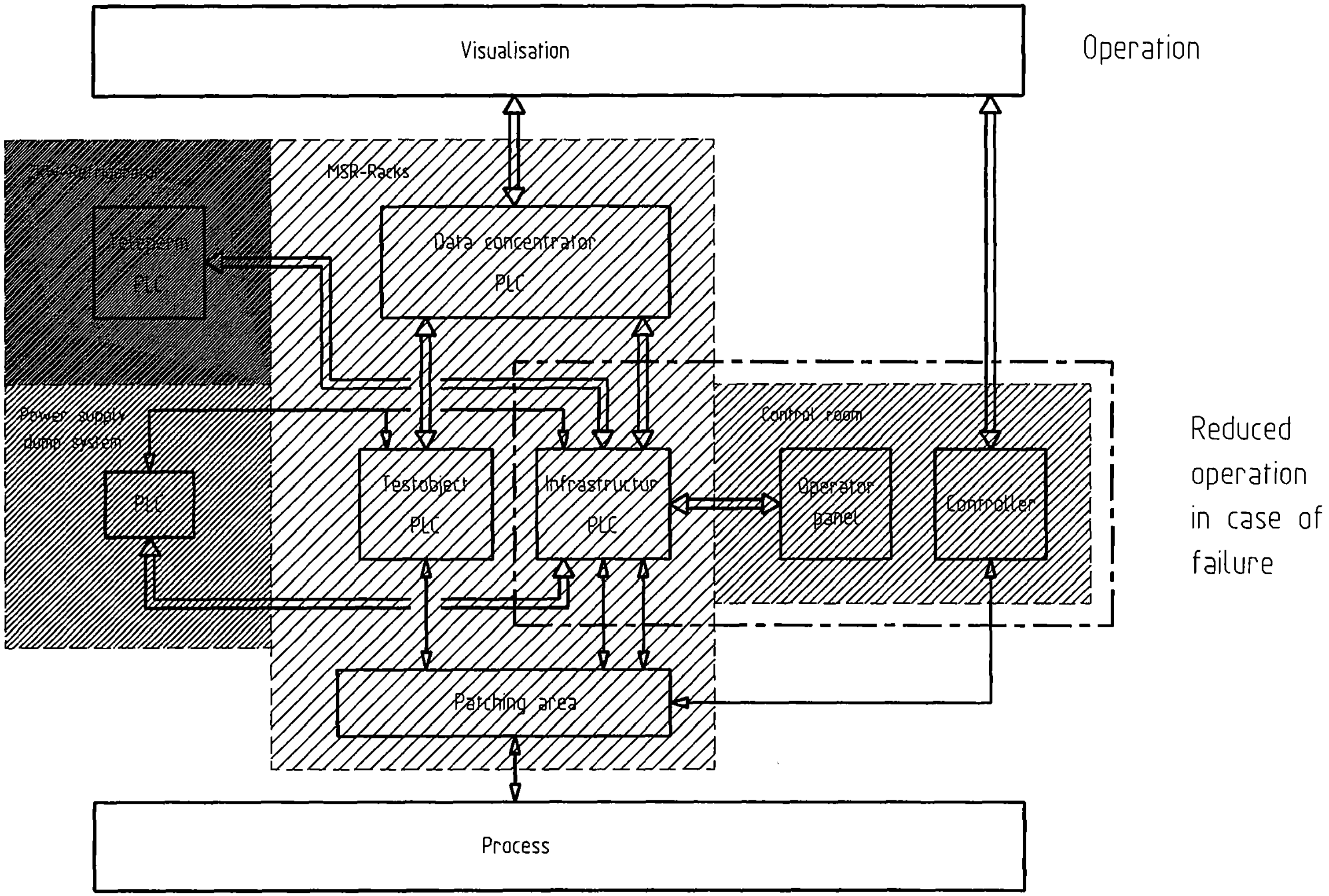


Fig. 3.5.2-1: The basic layout of the communication paths

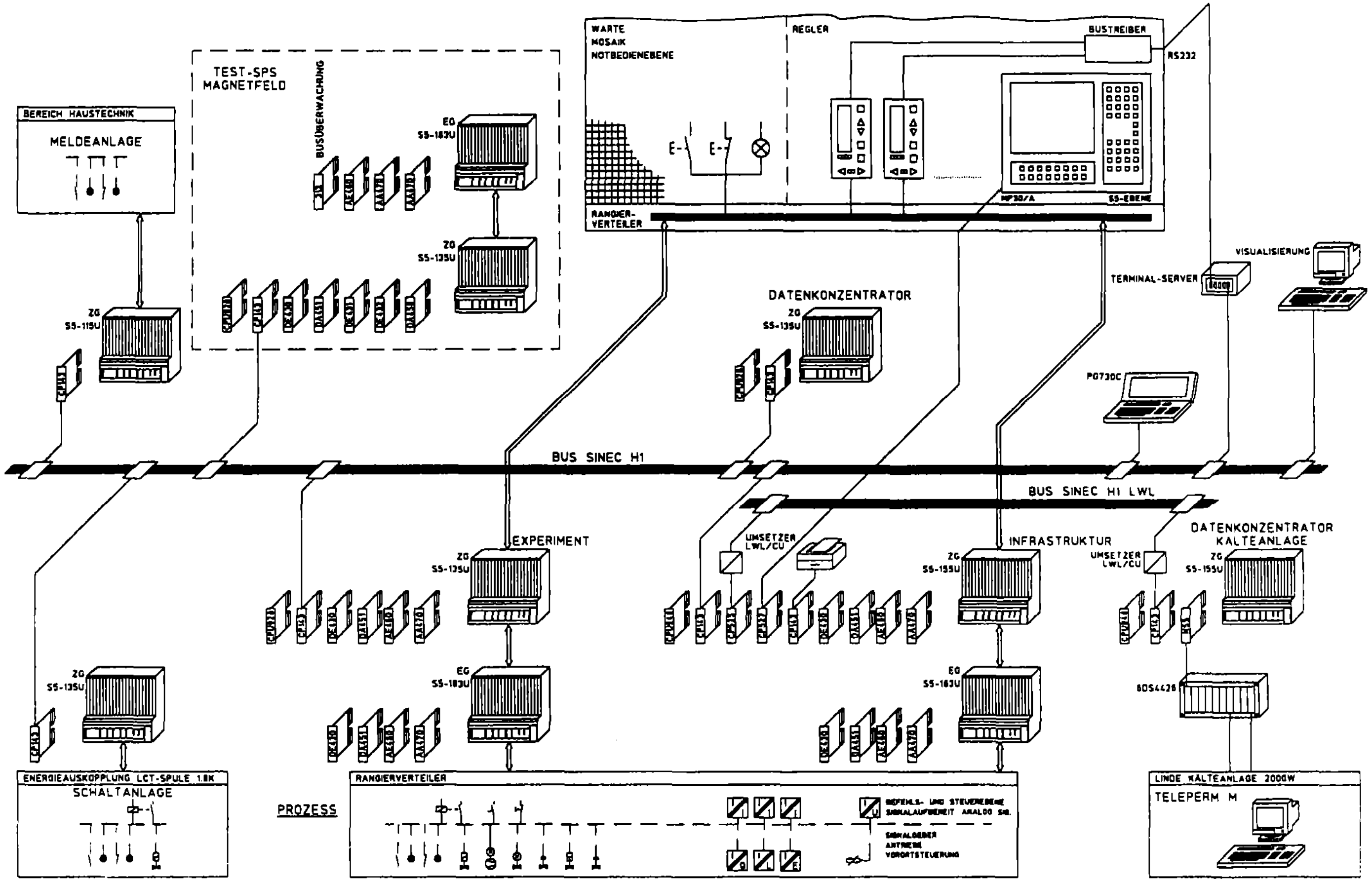


Fig. 3.5.2-2: The connection of the programmable controllers (PLC) to the bus SINEC H1

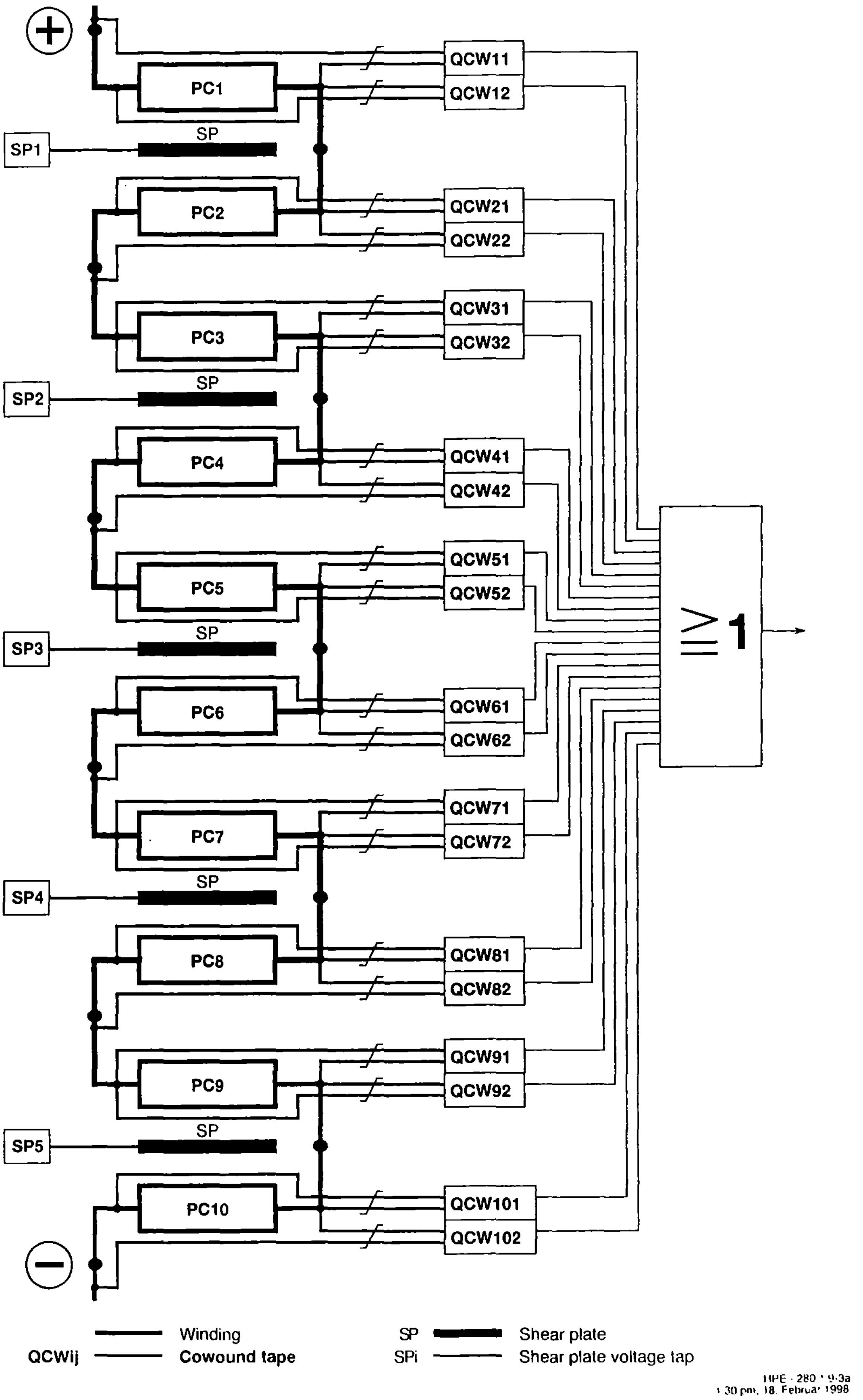


Fig. 3.5.3-1: The quench detection scheme of the TFMC

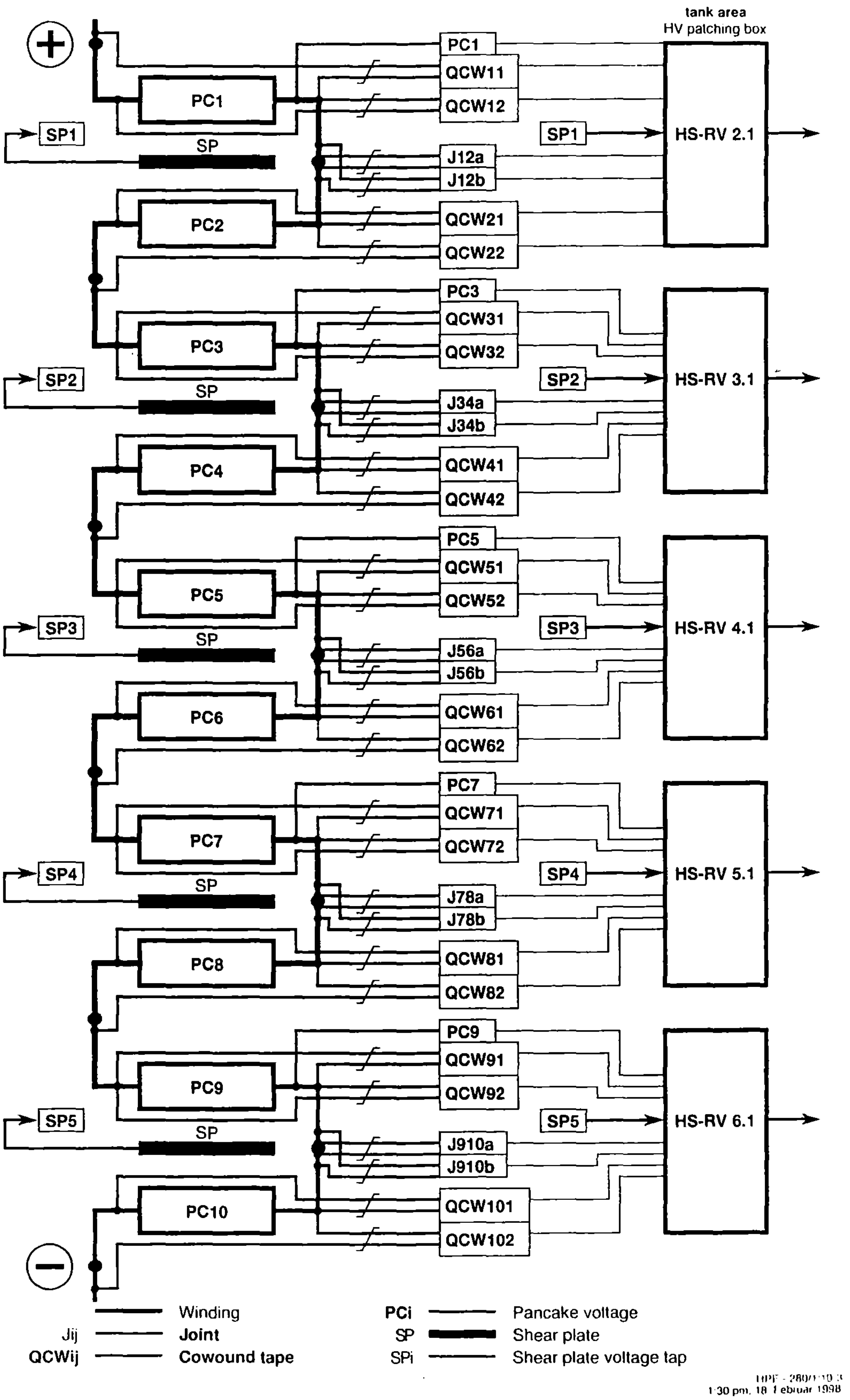


Fig. 3.5.6-1 : Patching scheme of the sensors at high potential

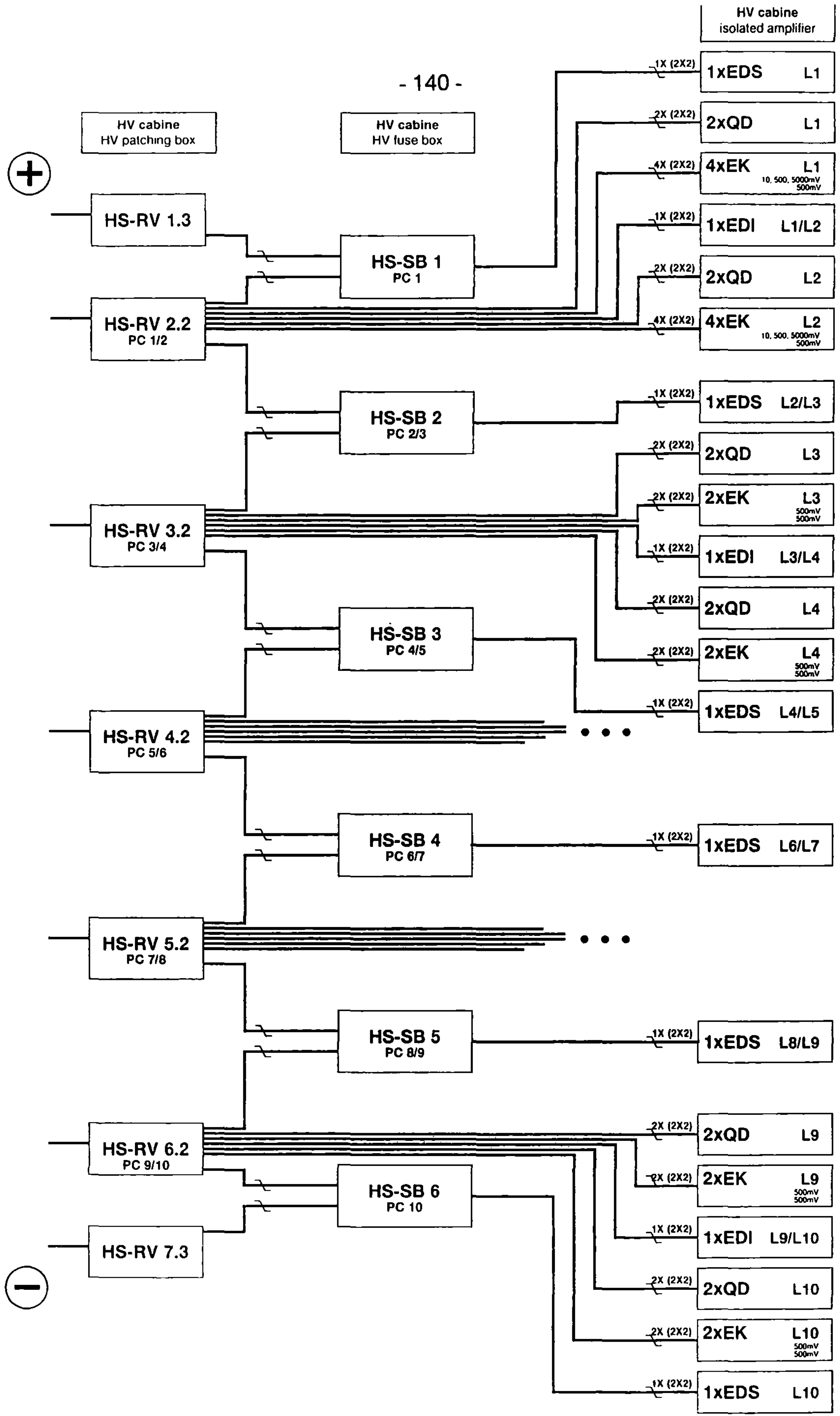


Fig. 3.5.6-2 : Routing of the signals to the isolation amplifiers

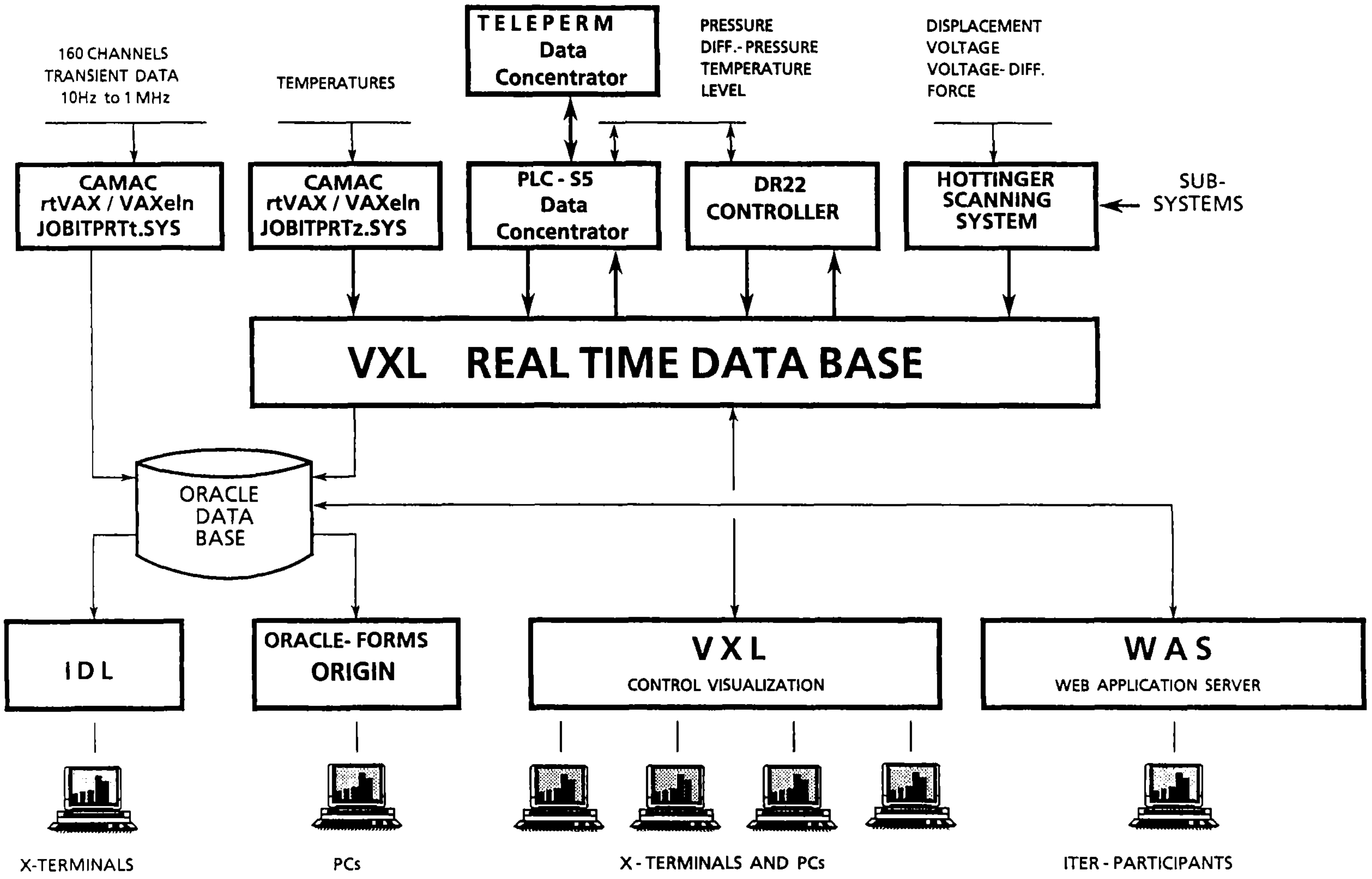


Fig. 3.5.8-1: Software configuration for the operation of the measuring and control of the TOSKA facility

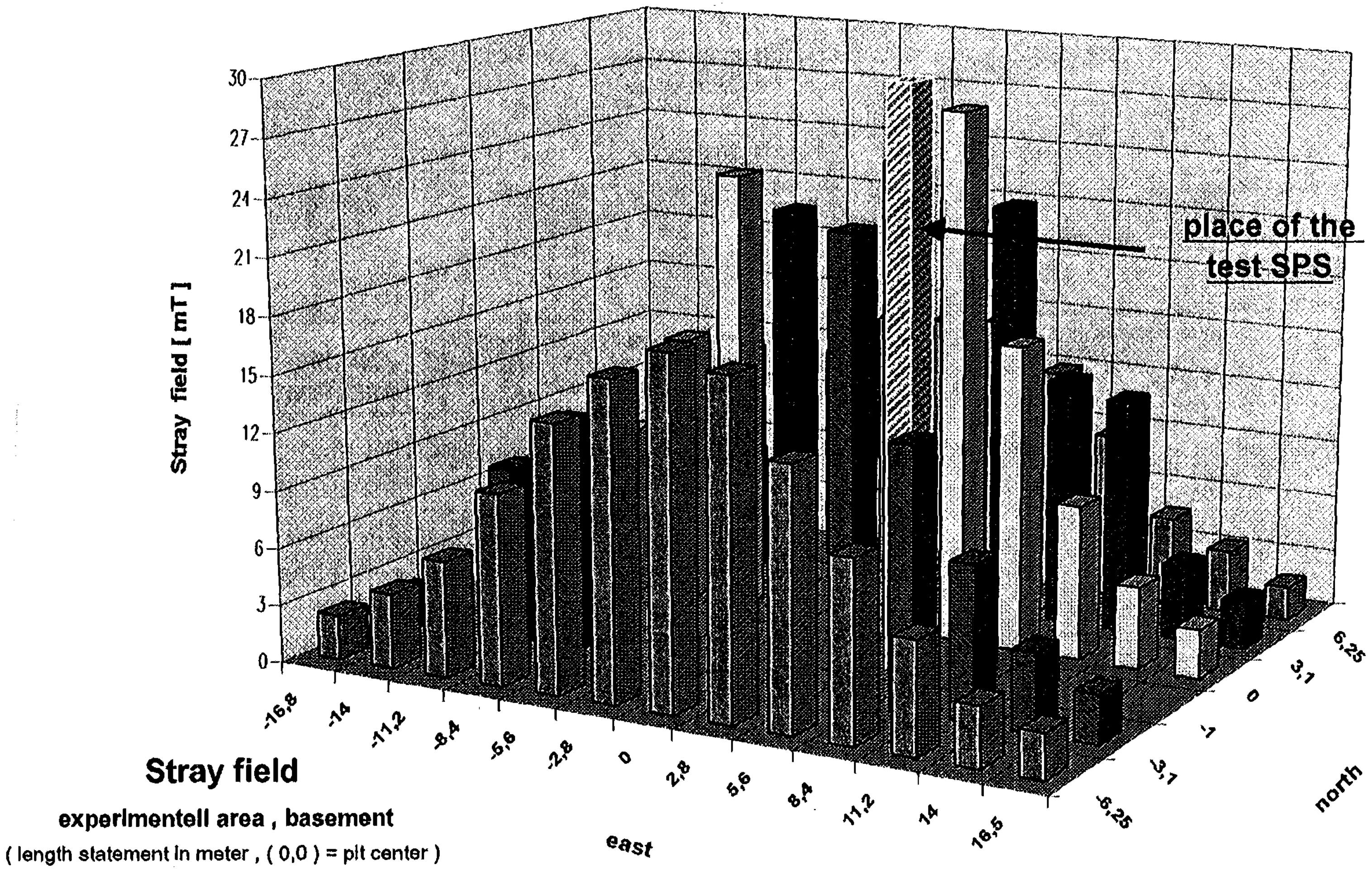
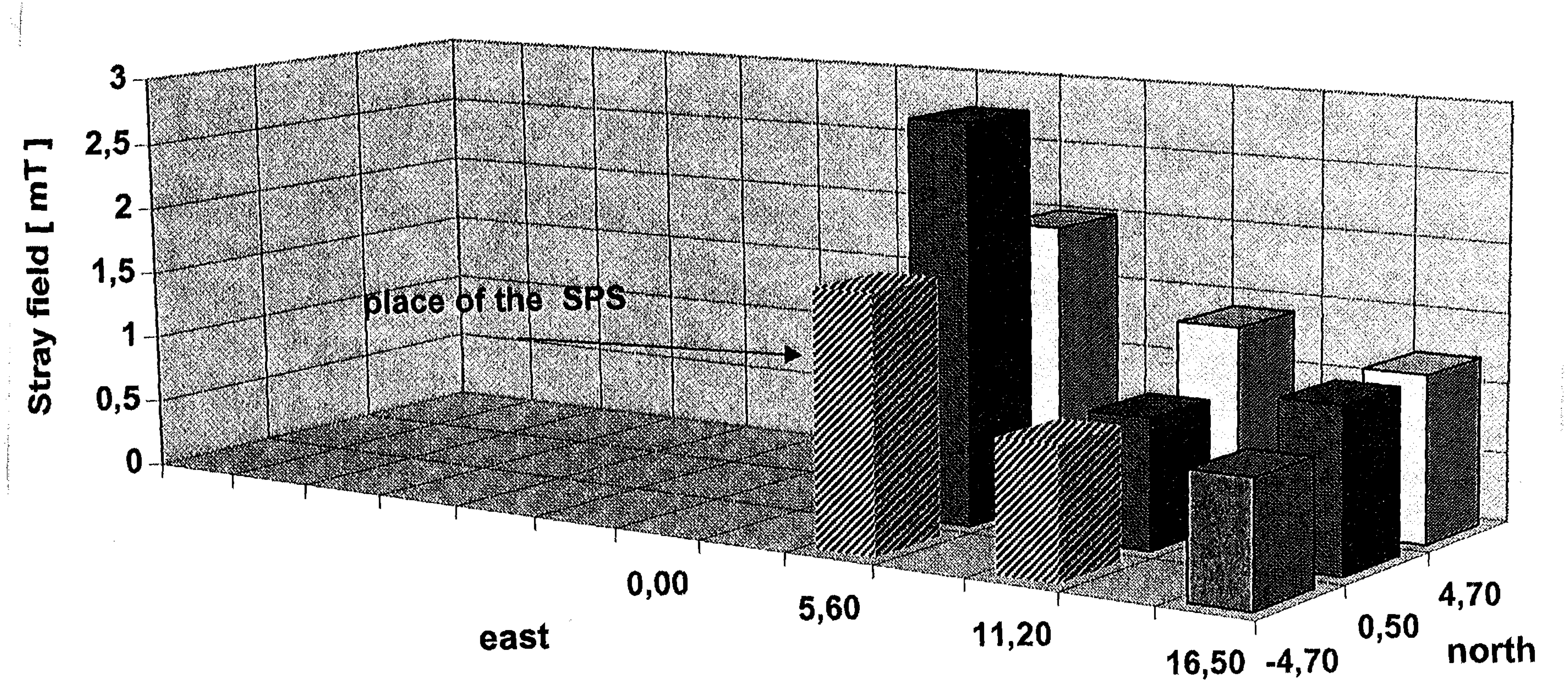


Fig. 3.5.9-1: Measured fringe field levels in the basement of the TOSKA facility. The field level of the PLC test position is indicated by a grey beam



Stray field

experimentell area , control room

(length statement in meter, (0,0) = pit center)

Fig. 3.5.9-2: Measured fringe field levels in the control room. The position of the PLC's is indicated.

3.6 TFMC installation

3.6.1 Test procedure

For saving time, the reduction of risk and getting results within the EDA it was decided to perform the test of the TFMC in two phases:

- Phase 1: Test of the TFMC alone by replacing LCT coil by an auxiliary structure (Fig. 3.6.1-1).
- Phase 2: Test of the TFMC with the LCT coil

The assembly of the TFMC and ICS beside the LCT coil including assembly of instrumentation and cooling lines have to be performed outside the vacuum vessel because the space inside is limited.

For Phase 1 the TFMC, ICS and auxiliary structure are assembled on the gravitational support, all electrical and thermohydraulic terminals have to be at the top of the test rig for connection to the facility or routing to the vacuum vessel feedthroughs. The configuration (TFMC + ICS + auxiliary structure) is lifted by the 80 t crane and the upgraded 65 t LCT cross head into the vacuum vessel (Fig. 3.6.1-2) and finally connected to the cryogenic supply system, current leads and data acquisition system.

In Phase 2 the configuration (TFMC + ICS +LCT) is lifted by the 80 t and 50 t crane and the 125 t cross head into the vacuum vessel

The TOSKA coordinate system used for defining the interface dimensions in the vacuum vessel are presented in Fig. 3.6.1-3.

3.6. 2 Installation procedure

The installation will be performed in the following simplified steps:

- Delivery of TFMC, ICS and assembly frame (for load distribution on floor < 10 t/m^2) as individual parts (Fig. 3.6.2-1)
- Uprighting and positioning of the ICS beside the LCT coil and adaptation of the ICS to the auxiliary structure and the gravitational support (Fig. 3.6.2-2
- Placing fiberglass sheets and resin onto the horizontal plates and screw the ICS onto the LCT coil during curing of the resin (Fig. 3.6.2-3)
- Disassemble the ICS and check the contact surface for sufficient contact area to the LCT coil case

- Assembly the ICS onto the LCT coil assembly frame in horizontal position after certain modifications of the frame
- Installation of the wedges onto the ICS
- Lifting of the TFMC, using a four chain hanger, into the ICS.
- Mounting of the upper wedges
- Alignment of the TFMC in the ICS and fixing of the TFMC for further installation steps
- Phase 1: Installation of the remaining sensors ,e.g., displacement transducer between ICS and TFMC as well as deformation measurements across the aperture of the TFMC and ICS (Phase 2: Installation of the remaining sensors ,e.g., displacement transducer between ICS and LCT coil).
- Completion of the piping work of the cooling system
- Up righting of TFMC and ICS together, using the lifting gear from the LCT coil and additional equipment to support ICS, busbars and HV cables with warm feedthrough connectors
- Place the ICS including TFMC beside the auxiliary structure (Phase 1) (LCT coil, phase 2), position and screw it to the auxiliary structure (Phase 1) (LCT coil, phase 2) and gravitational support
- Test of all sensor of the whole configuration and HV test of the TFMC winding outside the vessel
- Lifting the complete configuration, using LCT lifting gear (total mass < 65 t or the new lifting gear for 125 t (total mass > 65 t), into the vacuum vessel (Fig. 3.6.2-4). For the Phase 1 configuration (TFMC, ICS, auxiliary structure), shorter lifting rods are needed than for Phase 2 configuration (TFMC, ICS, LCT) if the 125 t lifting gear has to be used (Fig. 3.6.2-5).
- Install the tension rods and fix the configuration inside the vacuum vessel
- Install temporary connections for a vacuum leak test of the TFMC winding, TFMC case, ICS, bus bars and auxiliary structure
- Perform vacuum leak test
- Connect coil to the cryogenic system and perform the flow test
- Assembly of the cryostat extension including 80 kA current leads for TFMC coil and 20 kA current leads for Phase 2 with LCT coil

- Assembly and insulation of joints of bus bars type I and type II
- Connection of the current leads to the Al busbars of the 80 kA power supply (Phase 2 only: and of the LCT coil power supply)
- Connection to the He supply, recovery and relieve system
- Route HV and low voltage (LV) cables to the appropriate ports/feed-throughs
- Sensor, HV and leak test of the whole configuration inside the vessel
- Closing the lid and evacuate the vessel
- Final leak test according to the vacuum method

Details are given in [3.6.2-1].

3.6.3 Tools for Installation

The following special tools are necessary:

- Specific tools for installation and lifting of the TFMC test configuration are needed. The components are conventional constructions and need no development.
- Assembly frame for TFMC and LCT for distributing the 120 t over 12 m^2 (10 t/m^2) (delivery of AGAN).
- Lifting gear to connect the 50 t and 80 t crane, lift the weight of 125 t and allow an adjustment in order to reach an exact vertical position of the test configuration for installation into the vacuum vessel (delivery FZK).
- Gravitational support to connected the test rig with the three feet support on the vacuum vessel bottom. The design is presented in Fig. 3.6.3-1. The existing tools, e.g., assembly frame and lifting gear of the LCT coil were modified

3.6.4 References

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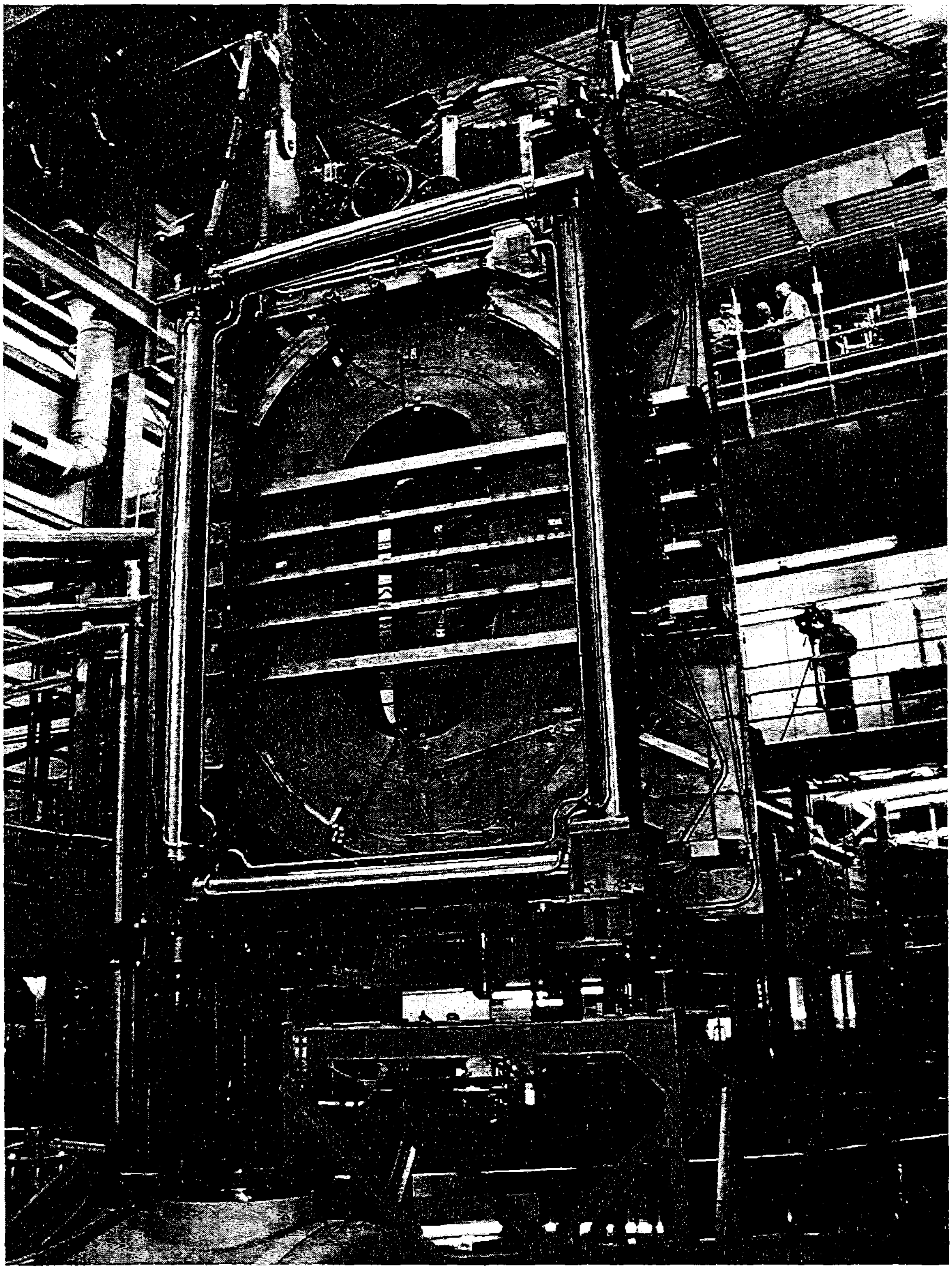


Fig. 3.6.1-1: The auxiliary structure replacing the LCT coil (Phase 1 test configuration)

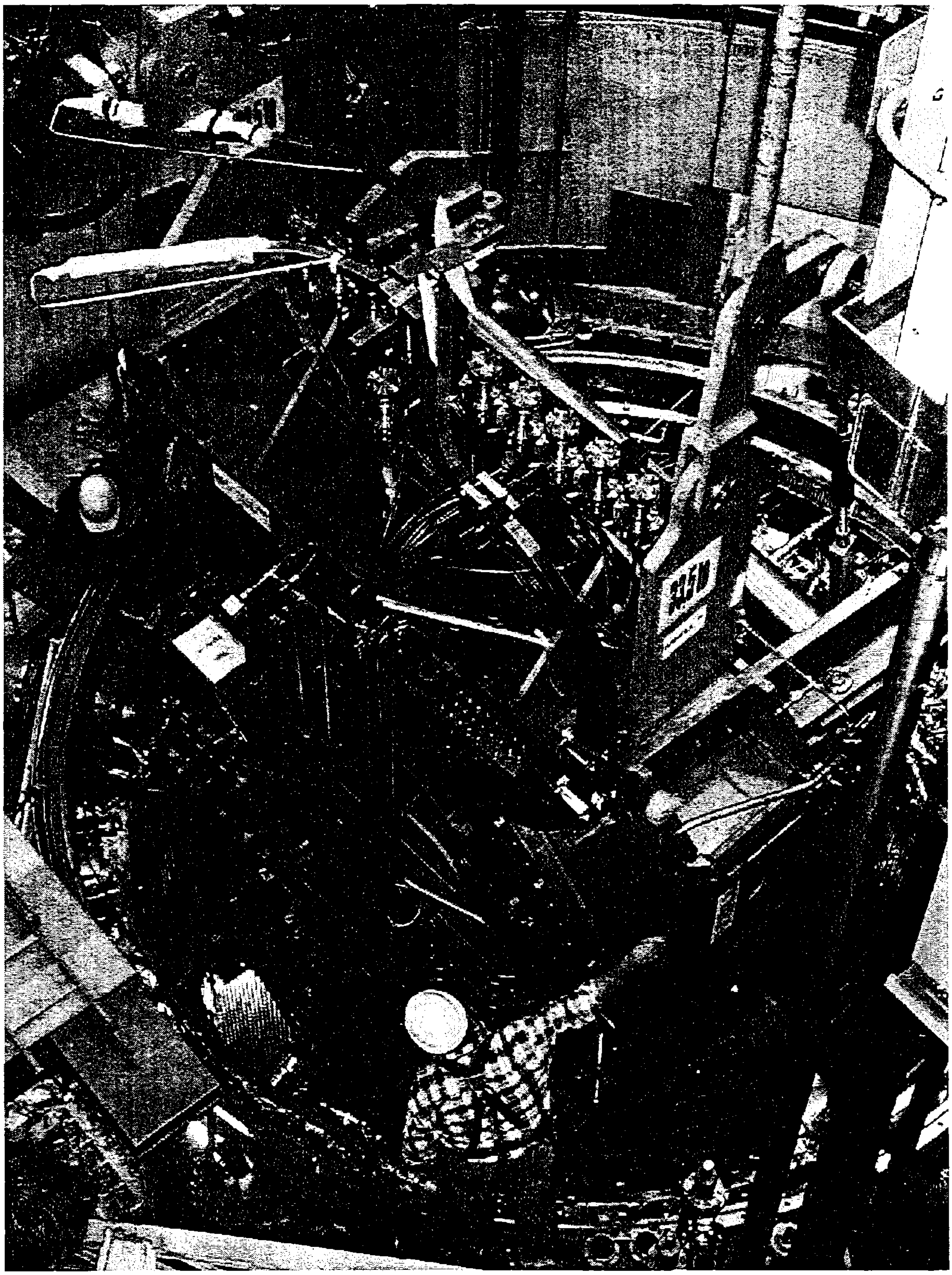
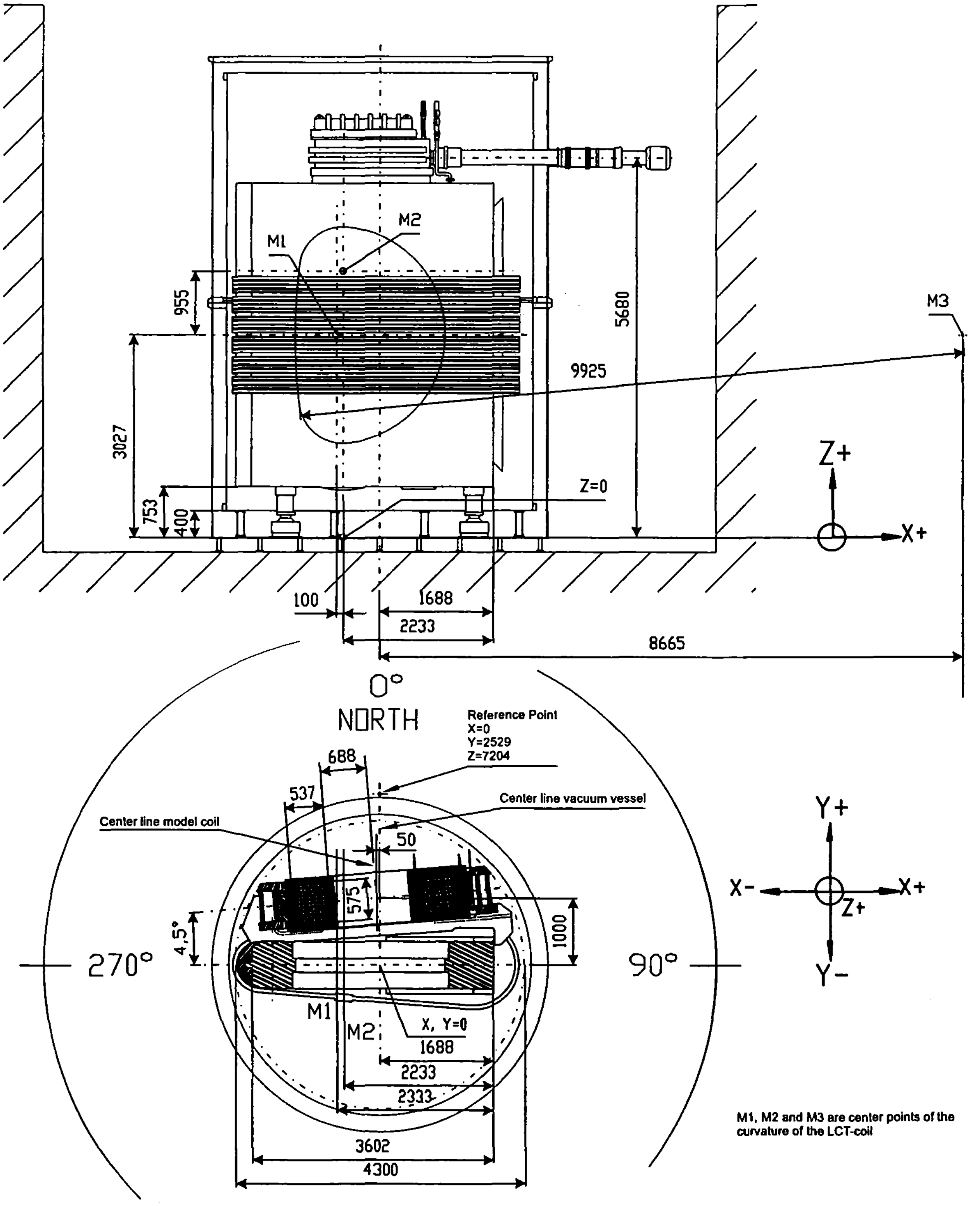


Fig. 3.6.1-2: The configuration (TFMC + ICS + auxiliary structure) is lifted by the 80 t crane and the upgraded 65 t cross head into the TOSKA vacuum vessel



M1, M2 and M3 are center points of the curvature of the LCT-coil

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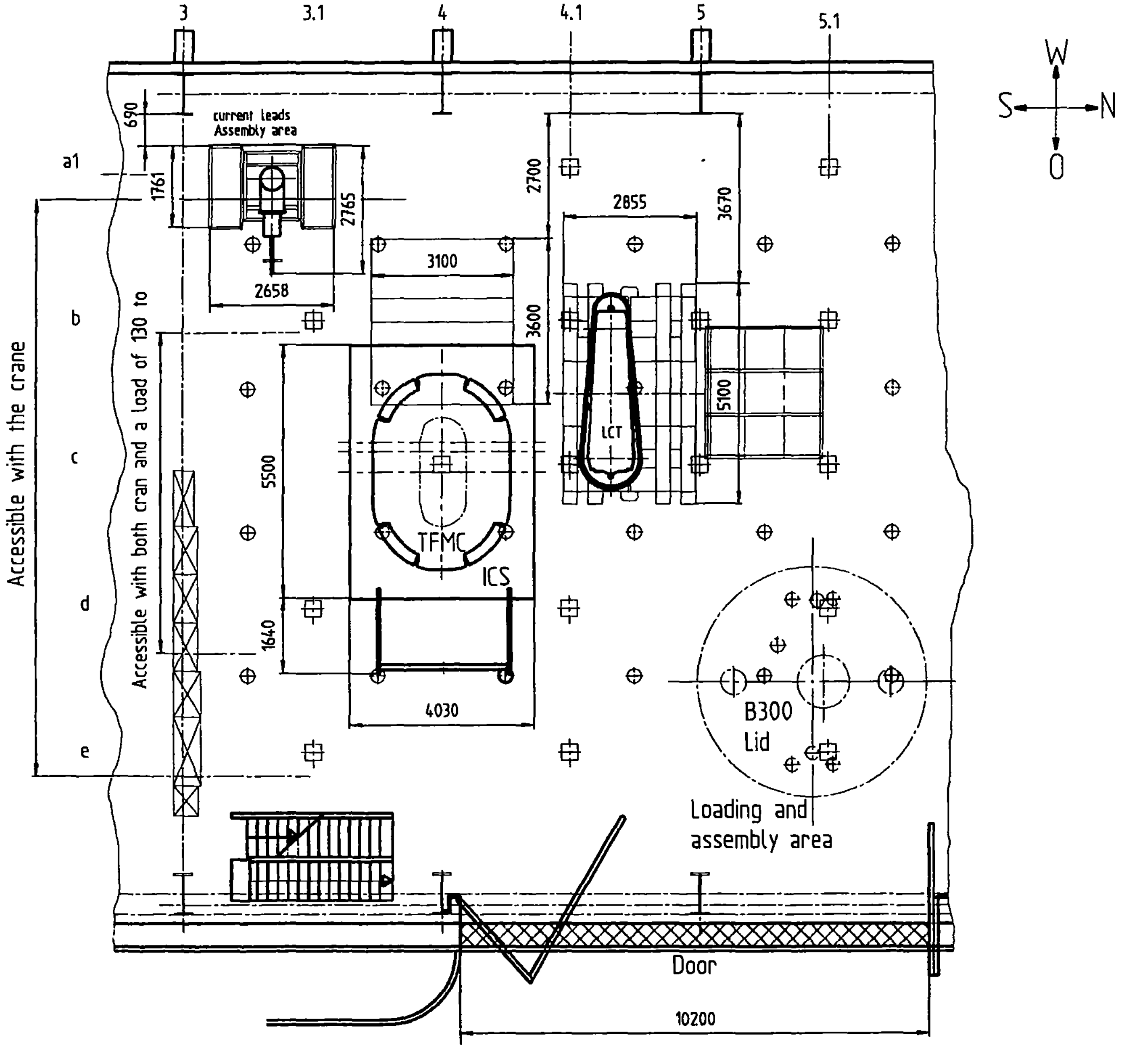
Fig. 3.6.1-3: The TOSKA vacuum vessel coordinate system for defining the interface dimensions (The height of the center of the 80 kA current lead flanges above the vacuum vessel bottom is 6550 mm).



Assembly step 1

Fig. 3.6.2-1 : The ICS and the LCT coil on the assembling frame in the TOSKA building

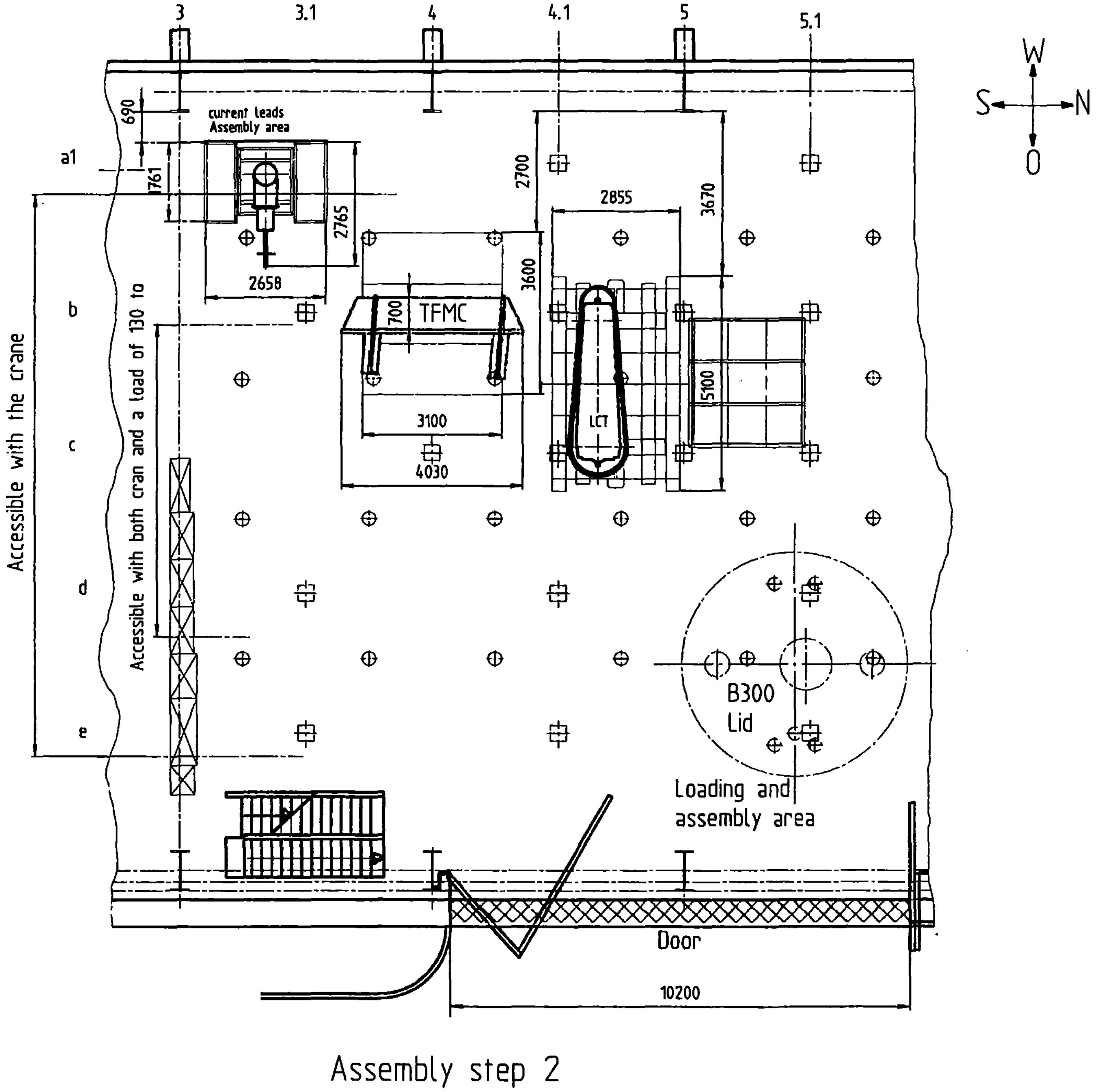


Fig. 3.6.2.-2 : The ICS after uprighting in vertical position

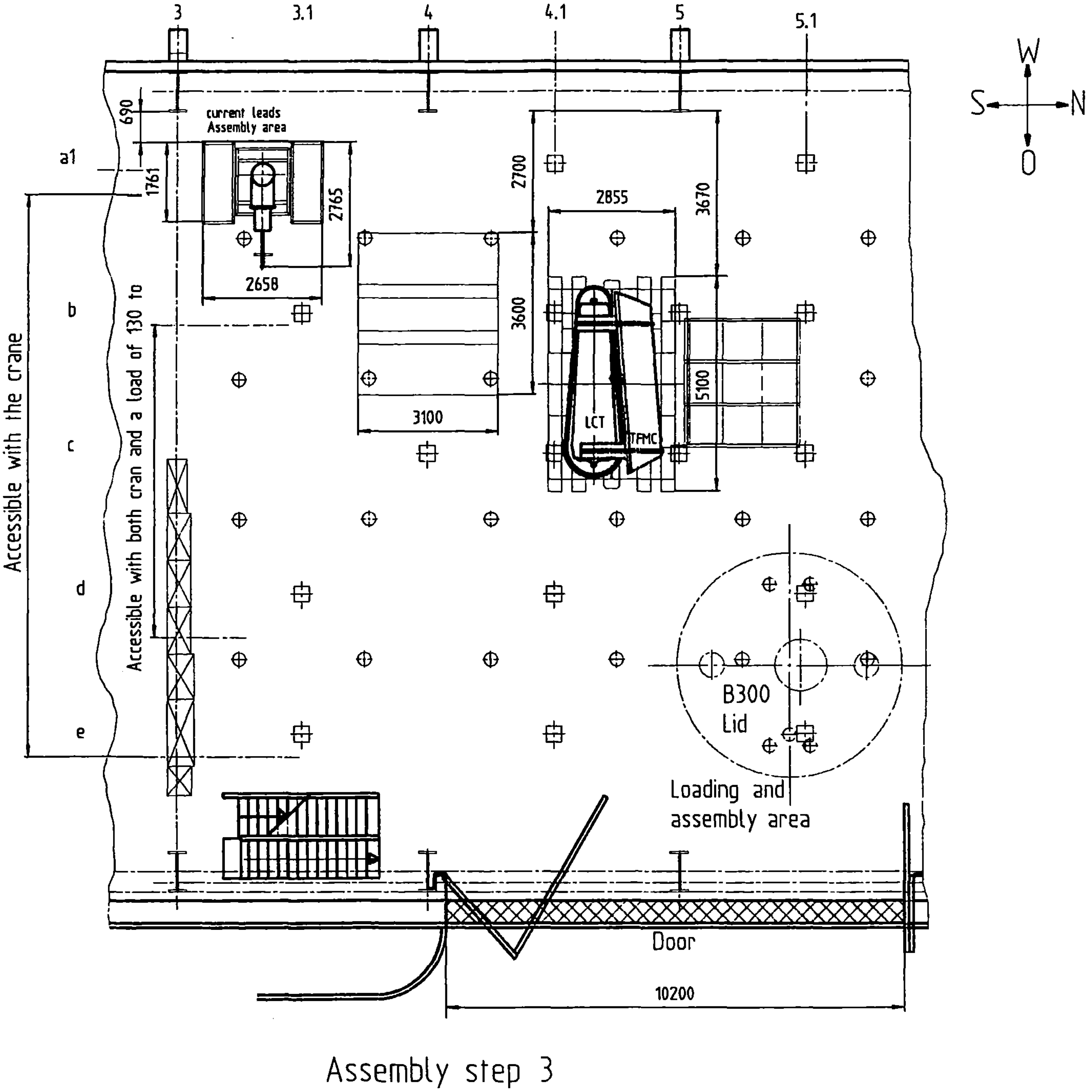


Fig. 3.6.2-3 : The ICS adjacent to the LCT coil for matching of the horizontal plates to the surface of the LCT coil.

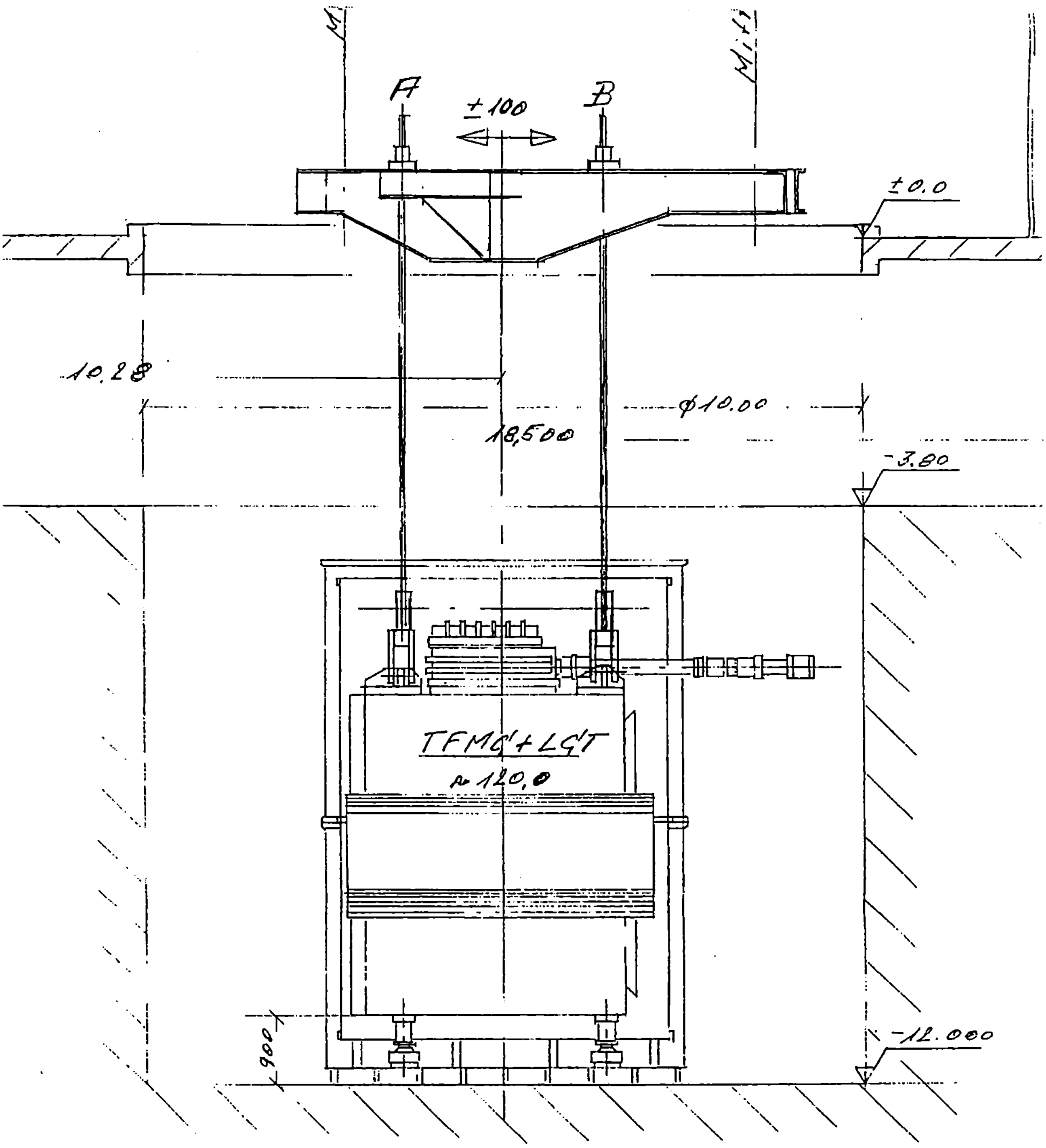


Fig. 3.6.2-1: The TFMC test configuration hanging on the lifting gear carried by the 50 t and 80 t cranes.

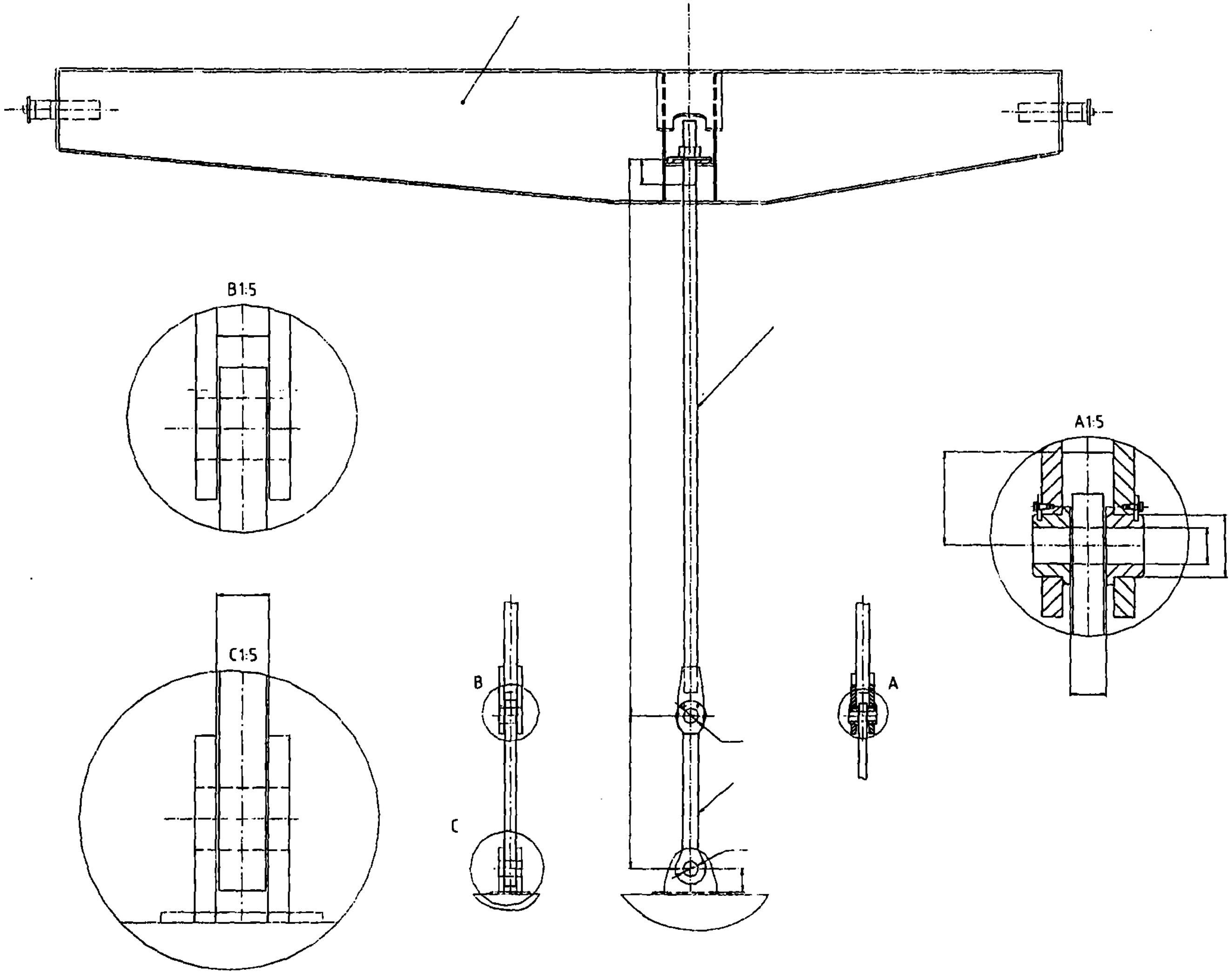


Fig. 3.6.2-5: 125 t cross head with lifting rods for Phase 1 (TFMC, ICS, auxiliary structure if mass > 65 t, short length) and for Phase 2 (TFMC, ICS, LCT, long length)

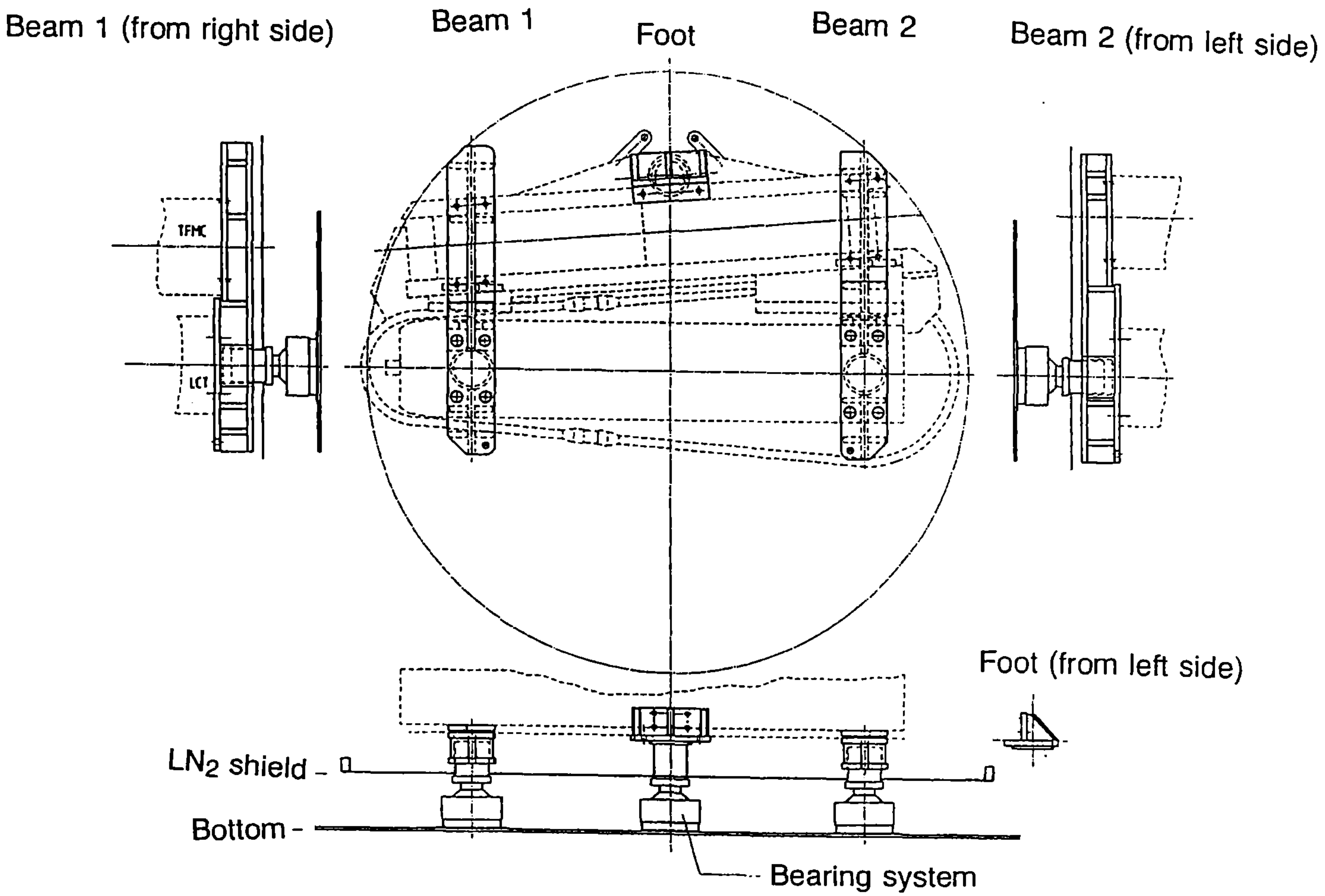


Fig. 3.6.3-1: The design of the gravitational support

3.7 Concluding remarks

The basic TOSKA facility as needed for testing of the TFMC was taken into operation one year after the conclusion of the POLO project in 1996 / 1997.

The basic facility consists of:

- The cryogenic supply system with two refrigerators (2 kW and 0.5 kW) including two forced flow circuits (3.5 K B250 and 1.8 K B1000, lowest operation temperature) with helium pumps
- A measuring and control system as well as a data acquisition at the state-of-the-art
- An electrical high current supply system up to 80 kA (Option 1) and tested switching circuits with arc chute breakers (Option 2) and a fast counteracting current switch (Option 3).
- A reliable background field generated by the EURATOM LCT coil (Option 2)
- Overhead cranes with 130 t lifting capability

These systems were commissioned and was used in the testing program steps of the TOSKA facility.

There was one further step in the facility preparation programme before the test of the TFMC namely :

- W 7-X Prototype coil test which was completed September 1999 with the its removal from the TOSKA vacuum vessel.

The components which have made available or to be adapted especially for the TFMC testing were:

- The 80 kA current leads (an extension of the 30 kA current lead development).
  Main development problems were solved in 1997. The consequence caused by the design change from the horizontal to the vertical installation position has been the need of cryostat extensions.
- The 80 kA dump circuit for the TFMC, the 20 kA power supply for the LCT coil and the change over of the 20 kA dump circuit from the 50 kA power

supply to the 20 kA power supply. The circuits were commissioned by a resistive copper coil up to 10 kA to assure the quality of the control and the timing of the switching sequence.

- Gravitational support and a lifting gear for the TFMC testing configuration: This is a mechanical engineering and construction work which was completed in time.
- A new software configuration for the visualization of the cryogenic supply system as well as measuring and control with data acquisition:

  This was completed. The completion of the WWW access of the data is in progress

The TOSKA facility has been completed for testing the TFMC end of 2000.

The ICS was delivered in June 2000 and aligned with gravitational support and the auxiliary structure. It was lifted in the TOSKA vacuum vessel for a trial fit to make sure that the necessary clearance is available. After that the support surfaces of the horizontal plates were matched with the surface of the LCT coil by epoxy resin impregnated glass sheets. At the upper and lower pads epoxy cast prints were taken for copy milling of the pads.

The TFMC was delivered January 2001, installed in the ICS, up righted and lifted in the vacuum vessel beginning March 2001. In the frame of the acceptance before the final installation a vacuum leak test is of the configuration is performed with temporary hydraulic connections for pressurizing the coil by helium.

The Phase 1, testing of the TFMC without LCT, coil will start in June 2001. The testing with LCT coil will be completed in 2002.

Acknowledgment

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Karlsruhe as well as European industry contributing to the completion of the TOSKA facility for testing the ITER TF model coil.

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