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Contract No. 240/86-6/FU-D/NET

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Abstract:

This report continues an earlier one on the possibilities of NET model coil testing in the TOSKA Upgrade facility at KfK. The investigation of a "Cluster Test Facility" and a "Solenoid Test Facility" is followed by the investigation of two further test arrangements. They are called "Twin Configurations". One common feature of both arrangements is that the EURATOM-LCT-coil delivers a background magnetic field. This coil should be operated at a temperature of 1.8 K and an enhanced current up to 20 kA compared to the LCT test where 3.5 K and up to 16 kA were the operating conditions. In one configuration the NET model test coil is adjacent to the LCT coil (ATC = Adjacent Twin Configuration), in the other one the NET model coil is inserted into the bore of LCT coil (ITC = Inserted Twin Configuration) either upright or with a 60° slope. The configurations are investigated with respect to their electromagnetic mechanical and thermo-hydraulic properties. The requirements for the necessary mechanical support structure of the LCT coil were computed. Installation and cooling of the whole system were discussed. The time schedule and the costs for the test facility modification were estimated. Advantages and disadvantages for the configurations were discussed with respect to feasibility of the test arrangement and operation.

Testmöglichkeiten für NET-Modellspulen in der TOSKA TWIN Konfiguration

Zusammenfassung

Dieser Bericht ergänzt einen früheren, in welchem Testmöglichkeiten für NET-Modellspulen in der TOSKA-Anlage vom KfK vorgestellt wurden. Die im ersten Bericht vorgestellte Cluster- und Solenoid-Anlage wird durch 2 weitere Anordnungen ergänzt. Beide sog. TWIN-Konfigurationen benutzen die LCT-Spule zur Erzeugung eines Hintergrundfeldes für den Test der Modellspule. Die LCT-Spule soll hierzu bei einer Temperatur von 1,8 K und Strömen bis 20 kA betrieben werden, was über den Auslegungsdaten von 16 kA und 3,5 K liegt und somit eine entsprechende Verstärkung des LCT-Spulengehäuses erfordert.

In einer Anordnung wird die Modellspule neben der LCT-Spule plaziert (ATC = Adjacent Twin Configuration). In der zweiten wird die Modellspule in der Bohrung der LCT-Spule (ITC = Inserted Twin Configuration) aufrechtstehend oder um 60° geneigt installiert. Die elektromagnetischen, mechanischen und thermohydraulischen Eigenschaften der Anordnungen wurden untersucht sowie die Installation und die Kühlung der Gesamtanlage ausgearbeitet. Weiter wurden ein Zeitplan erstellt und die Kosten für die Ergänzung der vorhandenen Testanlage für den Test von NET Modellspulen abgeschätzt.

Abschließend werden Vor- und Nachteile der Anordnungen hinsichtlich Realisierbarkeit und Betrieb diskutiert.

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1. Introduction

This report continues an earlier one on the possibilities of NET model coil testing in the TOSKA Upgrade facility at KfK [1]. There the major task of the fusion technology programme to develop a toroidal field (TF) magnet system for NET/ITER is described and is not repeated in this report.

NET/ITER requires superconducting magnets of about 8 m x 11 m bore and a magnetic field of about 11 - 12 T. For such fields the use of Nb_3Sn superconductors is the reference choice.

One step on the development path is the coil technology verification test. After conductor development prototype industrial lengths of the conductor will be fabricated. Then the next step is the manufacture of model coils. These coils should be tested in a facility in order to prove their feasibility, operation, and reliability.

In [1] two possible test arrangements have been discussed:

- a so-called "Cluster Test Facility", where the EURATOM and Swiss LCT coils are used as background field coils for two model coils out of TF-conductors, and

- a so-called "Solenoid Test Facility", where in addition to two model coils out of TF conductors another model coil out of a poloidal field (PF) conductor is integrated in the test facility. No use of an LCT coil was foreseen in this case.

Both possible arrangements were compared with respect to:

- further use of already existing equipment at KfK,

- technical difficulties for installation of the model coils into the facility,

- operation flexibility during test and in case of a possible failure,

- costs,

- manpower, and

- time schedule.

The installation would be possible but very difficult in case of the cluster configuration, but with respect to operation flexibility the cluster solution was preferred.

The result of this comparison was that the costs for both configurations were jugded to be high and therefore it was emphasized to search for a less expensive solution.

In the meantime LCT results of the EURATOM coil surpassed the expectations, e.g. 9 T in single coil operation and 9.2 T in full torus operation. In view of installation difficulties and a possible subcooling of the EURATOM coil ($\geq$ 1.8 K) it was decided to explore an arrangement of a so-called "Twin-Test". In this test arrangement the EURATOM LCT coil delivers the background field for the NET model coil to be tested. This model coil is built up by double pancakes wound with different conductors or only one. They have usually slightly different current densities and also different geometric dimensions. To simplify the design calculations only one conductor is chosen which then defines current density and the dimensions of the winding pack.

This study has been performed as an extension of the NET contract No. 240/86-6/Fu-D/NET. It together with the first one should broaden the base for further decisions concerning the fusion technology programme step "NET-TF Model Coil Testing".

[1] J.Erb, A. Grünhagen, W. Herz, I. Horvath, K. Jentzsch, P. Komarek, K. Kwasnitza, E. Lotz, S. Malang, C. Marinucci, W. Maurer, G. Nöther, G. Pasztor, A. Peters, A. Roeterdink, C. Sborchia, A. Ulbricht, A. Vogt, P. Weymuth, G. Zahn, NET Model Coil Test Possibilites, Final Study Report, KfK 4355, November 1987.

2. The goals of the test

The NET development programme and the different conductors for the NET model coils to be tested are described in detail in [1]. In this report only the test goals and the NET requirements for TF-conductors are repeated.

2.1 General objectives of the model coil test programme

The primary goals of the model coil test programme include [2] :

- development of the entire coil manufacturing process including coil winding of double pancakes, conductor termination and joints, coil insulation, assembly, vacuum impregnation, current leads, feedthroughs and instrumentation,

- verification of the success of the industrial manufacturing process by testing the coils under operation as close as possible to NET conditions,

- validation of design codes for stress analysis and quench behaviour and validation of predictions of performance made on the basis of sub-size component tests,

- performance of tests that can only be made in a large coil test and that may point up synergistic effects,

- selection among the conductor options based upon test performance, manufacturing, and cost evaluation.

The model coils should have geometrical dimensions which are representative for NET coils in certain limits. In its test bed the model coil should reach field and stress values which are either identical with those of the NET coils or allow a scaling. The model coils should demonstrate in their test bed that the manufacturing techniques of conductor and coil are ruled by engineering standards and are reproducible.

The general goals mentioned above cover a quantity of objectives which have to demonstrate the availability of the developed technology for application.

The objectives can be divided into two major groups:

- direct test objectives:

The direct test objectives are determined by the specifications of the final product: the model coil. The specifications are measurable facts characterizing the model coils. Some of them are verified by the use of special equipment. They will be discussed in detail in the following sections.

There are components which can't be tested sufficiently without the model coil or which are needed for the operation of the model coil. All electrical and thermohydraulic protection systems of the model coils belong to these objectives. The dynamic behaviour of such systems is strongly correlated to the coils and the arrangement of the coils. Another item is the optimization of thermohydraulic operation parameters which are needed for the design of an economic cryogenic system for the NET magnets.

- indirect test objectives:

The manufacturing of the conductor and the coils requires an extended development programme in order to obtain a reproducible production process which is then handled by the quality assurance program. The model coil manufacturing is partly a test of the process for the NET coil production. Therefore this process is indirectly tested if the model coil reaches its specifications.

2.2 NET test requirements [2]

Tests for the TF model coils can generally be divided into two categories, namely tests at standard NET operating conditions and tests to determine the limits of operation. They should simulate as close as possible the actual NET operating conditions including magnetic field, current, strain and transient operation.

The coils should be designed and instrumented to extract as much information as possible. However, the experimental nature of these coils and the imposed instrumentation should not interfere with the safe operation of the coils or otherwise compromise the chances for a successful mission.

All test requirements for the model coils are based upon the assumption that a significant basis of knowledge of conductor performance and parameters has been determined by exhaustive tests on sub-size components and full-size conductors in short lengths. Results of tests which should be available for the prototype conductor and components include (but are not limited to):

- critical current as a function of magnetic field, temperature and strain (longitudinal, transverse, bending) ideally for the full-size conductor,

- complete characterization of the AC losses as a function of B, $\dot{B}$, ΔB and I for three field orientations (2 transverse, 1 longitudinal) and various combinations thereof,

- stability measurements as a function of mass flow rate, temperature, current, magnetic field and energy disturbance length and duration for the TF conductor and maximum current and field ramp rates (or AC operation), and

- quench and recovery behaviour as a function of operating current, field, temperature and mass flow rate including measurement of maximum pressure and temperature and quench propagation velocity as a function of dump delay time, and dump time constant.

To the extent these tests can't be completed, it becomes imperative that they have to be carried out in the model coil test. For example, it might be difficult to get sufficient data on quench behaviour from a sub-size test facility thus requiring more extensive testing in the model coil.

The test requirements of the TF model coils are the following:

- The coils should be operated at the nominal NET conditions including current (16 kA), peak magnetic field (11.4 T), and global winding pack peak stress levels. The requirement to operate near NET stress levels may require the use of an external loading structure.

- Strain measurements should be used for comparison with results of FEM calculations for verification of the codes and measured or estimated global winding pack parameters.

- The DC limits of operation should be determined by measuring the critical current as a function of magnetic field and temperature.

- AC loss calculations and measurements should be verified by exposing the coil to AC or pulsed magnetic fields either self-generated or created by an external source.

- Stability calculations and measurements should be verified by exposing the coil to sudden energy inputs at different mass flow rates to explore the limits of stable operation.

- Quench tests should be performed in order to verify the quench codes. Tests of the integrity of the coil during quench and dumping.

The target test values for the TF model coils are given in Table 2.1.

Table 2.1: Target test values for NET TF model coils

Parameter	Unit	Value
Maximum Field at Conductor	(T)	11.4
Operating Current	(kA)	16
Peak Winding Pack Stresses		
- Radial	(MPa)	-40
- Toroidal (Axial)	(MPa)	-140
- Hoop	(MPa)	140
- Shear	(MPa)	30
Maximum Rate of Field Change		
- Normal Operation	(T/s)	0.55
- Plasma Disruption	(T/s)	1.0*
Nuclear Heating in Winding Pack		
- Average	(mW/cm^3)	0.05
- Peak	(mW/cm^3)	0.3

* Estimate, to be confirmed by further analysis.

[2] J. Minervini, NET-Team, NET/87/TE-100-R-04, 29.06.1987.

3. Performance of the Euratom LCT coil

3.1 Data of Euratom LCT coil

The performance of the LCT coils is described in [3]. The main characteristic features of the EURATOM LCT coil and its conductor are given in Tables 3.1-1 and 3.1-2. Fig. 3.1-1 shows the winding cross section of the coil. Table 3.1-3 contains the input data for the computation of electromagnetic properties as fields, forces, and inductances. On behalf of that the computer code EFFI [4] was used and TOKEF [5] generated the input.

For calculation purposes (only rectangular cross sections are allowed), the LCT coil was divided in an outer and an inner part as shown in Fig. 3.1-1. The center line is composed of arcs; their data are given in Table 3.1-3 and were used for computation during the LCT tests in Oak Ridge, USA.

The repetition of the coil data in this report is intentionally and has the following reasons:

- the operation temperature will be decreased from 4 K to 1.8 K,
- the current will be increased above the 15.95 kA already reached,
- the field level will consequently increase (up to 11 T), and
- most important is the rise of the forces which have to be sustained by the coil.

The quoted data in the tables enable everybody to follow the calculation and argumentation lines of this report.

Table 3.1-1: Main characteristic features of the EURATOM coil

	Unit	
Superconductor		NbTi
Rated current	A	11,400
Number of turns		588
Winding method		Flat wound two in hand in 7 double pancakes
Conductor length (total)	m	6526
Grading		none (one conductor)
Overall rated winding current density (3.8 K, 8 T)	kA/cm^2	2.40
Self-inductance	H	1.59 (calculated), 1.57 (measured)
Maximum rated field at conductor	T	8.11
Self-stored energy	MJ	103
Ampère turns	MA	6.7
Structure material		SS DIN Wkst. No. 1.4429 (similar SS 316 LN)
Assembly		Bolts with seal welding
Winding total weight	kg	18,200
thereof: SS	kg	7144
Cu	kg	8004
SC	kg	1050
Epoxy and solder	kg	1990
Case total weight	kg	20,600
thereof: SS	kg	20,300
Epoxy and filler	kg	300
Total weight	kg	39,000
Cooling method		Forced flow cooled
Operating temperature	K	3.8
Operating pressure	MPa	0.6 - 1.5
Test pressure	MPa	2.5
Number of cooling channels		28
Cooling channel structure		2 in parallel
Helium inventory in winding	ℓ	630
Helium inventory in case	ℓ	33
Current density of copper stabilizer	kA/cm^2	8.26
Joule heating in stabilizer at 8 T	W/m	518
Design dump voltage	kV	2.5
Test voltage	kV	12

Table 3.1-2: Main characteristic features of the EURATOM conductor

	Unit	
Superconducting material		NbTi
Conductor configuration		
Dimension	mm x mm	40 x 10
Aspect ratio		4.0
Cross section area	mm^2	400
Corner radius	mm	2
Material cross sections		
NbTi	mm^2 (%)	29 (7.25)
Cu	mm^2 (%)	138 (34.5)
SS	mm^2 (%)	134 (33.5)
He	mm^2 (%)	95 (24.75)
Solder		Negligible
Current design		
Nominal current (8 T, 3.8 K)	A	11,400
Critical current (8 T, 4.2 K)	A	> 15,000
NbTi current density (8 T, 4.2 K)	kA/cm^2	39.3
Copper (total) current density	kA/cm^2	8.26
Nominal overall conductor		
current density	kA/cm^2	2.88
Stability design		
Material		
Resistivity at 4.2 K, 8 T		Strand copper
0.2 % yield strength	Ωcm	5.5×10^{-8}
Superconductor cable design	MPa	210
Cable type		
Cable size		Flat, Roebel transposed
Strand dimensions	mm x mm	38.4 x 7.2
Number of strands	mm x mm	2.35 x 3.1
Twist pitch		23
Copper/superconductor ratio	mm	400
Filament diameter		4.7:1
Number of filaments	µm	45
Twist pitch		774
	mm	35

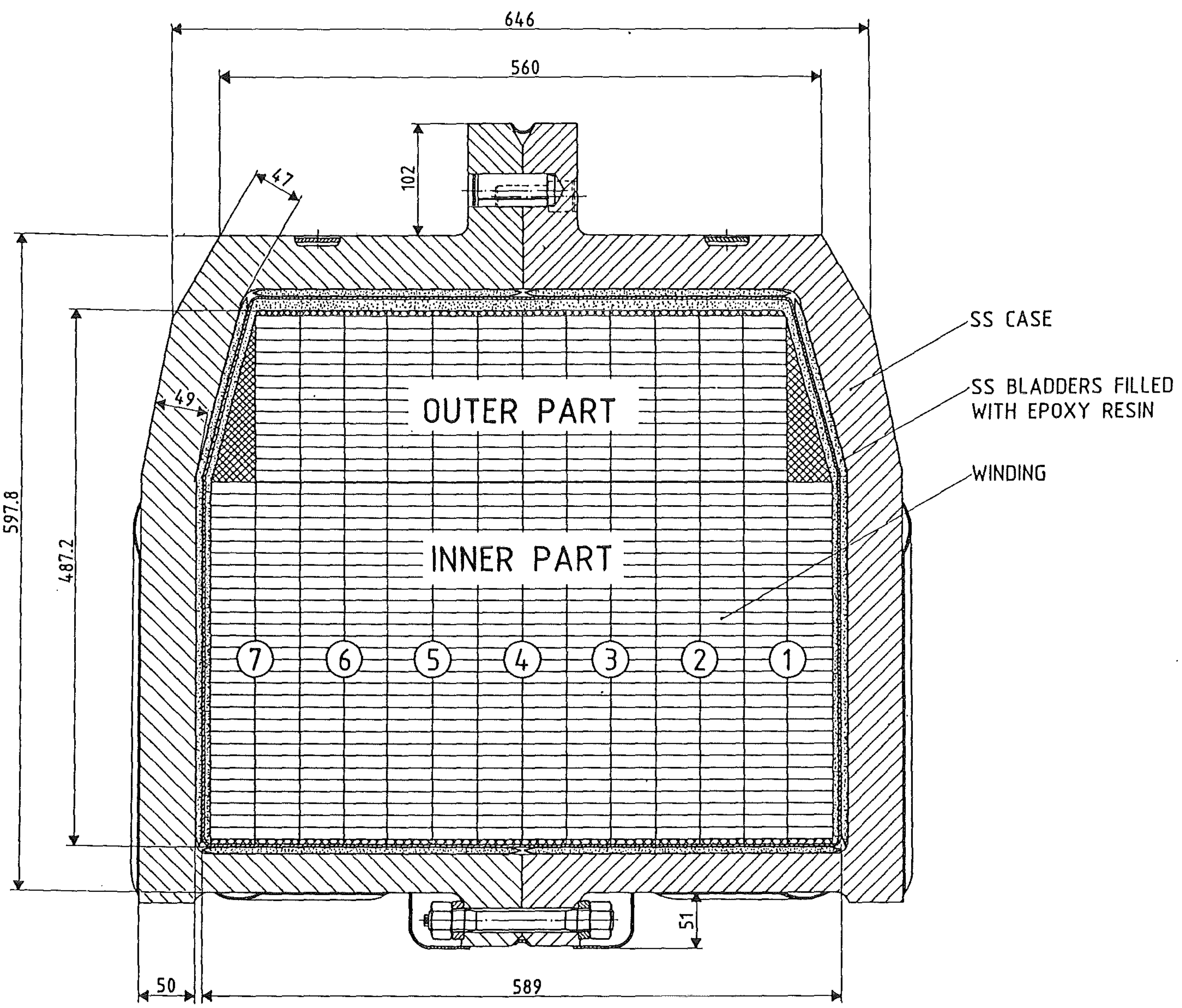

Fig. 3.1-1: Winding cross section (The numbers (1) to (7) denote the double pancakes).

Table 3.1-3: Input data for computation of EURATOM LCT coil properties

Center line data for outer part of LCT coil in the local coordinate system

ARC No.	Radius [m]	X-coordinate [m]	Z-coordinate [m]	Φinitial [degree]	Φend [degree]
1	2.1451	0.	0.	0.	84.0
2	1.1855	0.1003	0.9543	84.0	174.0
3	10.317	9.1818	0.	174.0	186.0
4	1.1855	0.1003	- 0.9453	186.0	276.0
5	2.1451	0.	0.	276.0	360.

Center line data for inner part of LCT coil in the local coordinate system

ARC No.	Radius [m]	X-coordinate [m]	Z-coordinate [m]	Φinitial [degree]	Φend [degree]
1	1.8944	0.0	0.	0.	84.0
2	0.9348	0.1003	0.9543	84.0	174.0
3	10.0663	9.1818	0.	174.0	186.0
4	0.9348	0.1003	- 0.9453	186.0	276.0
5	1.8944	0.0	0.	276.0	360.

Additional data

	Unit	Outer Part	Inner Part
Axial width DA*	m	0.4992	0.5826
Radial thickness DR*	m	0.16	0.3414
X-coordinate of center	m	- 0.6	- 0.6
Y-coordinate of center	m	0.6	0.6
Turn number		168	420
Overall current density for 11.4 kA*	A/cm^2	2397.84	2407.24

* Values are taken after manufacturing of winding pack, therefore slight differences to design values occur.

3.2 Performance of the Euratom coil during tests

A comprehensive description of the test results of the LCT experiment is given in the LCT Summary Report [3]. Table 3.2-1 summarizes the main achievements reached by the EURATOM coil during the test series.

The rated current of the coil of 11.4 kA was exceeded several times. The highest current of 15.95 kA was reached in a single coil test and corresponded to the critical current extrapolated from the short sample measurements. The operation of the coil at its critical current of the short sample value produced a maximum magnetic field at the conductor of 9 T in the single coil test. The highest field of 9.2 T was reached in a full torus test.

The highest observed equivalent stress of 295 MPa on coil case was reached in the high current single coil test. The highest overall radial force of 57 MN was observed in the maximum final torus test. The out-of-plane load tests led to 26.6 MN maximum out-of-plane force and 165 MPa equivalent stress. The observed stress levels correspond to those expected from the finite element calculation for the most of the load cases. Despite of the high forces and stresses no damage of the coil occurred demonstrating a successfull mechanical design of the coil.

The operating limits of the coil were explored and determined by current sharing temperature measurements. The stability of the coil was demonstrated; there was no unintentional quench, even the coil was operated beyond the region of the cryogenic stability. A very remarkable experiment demonstrated the reliable operation of the coil even without coolant flow in the winding and case. The coil stayed for about 10 minutes at 11.4 kA without flow and did not quench; afterwards it was ramped down within 50 minutes to zero current, and also no quench occurred.

As general conclusion it can be stated, that the EURATOM coil showed a mature engineering design and that the NbTi conductor technology with forced flow cooling reached engineering standards.

Table 3.2-1: Performance of the EURATOM LCT coil during tests in Oak Ridge.

Objective	Achievement
Normal and Extended Test Programme	Successfully passed
	Current / Field
High Current Single Coil Test	15.95 kA, 9 T
High Field Torus Test	12.99 kA, 9.1 T
Maximum Final Torus Test	12.08 kA, 9.2 T
	Forces and Stresses
High Current Single Coil Test	295 MPa on coil case (Highest observed equivalent stress)
Maximum Final Torus Test	57 MN highest overall radial force
Out-of-plane Load Test	26.6 MN highest out-of-plane force, 165 MPa highest observed maximum equivalent stress
Operating Limits	Explored and determined by current sharing temperature measurements
Hot Spot	Determined by expelled Helium gas
Stability	Demonstrated (no unintentional quench)
	Demonstrated even without flow in the winding and case (~ 10 min at 11.4 kA, then ramp down within 50 min to zero current)
NbTi conductor Technology with forced flow cooling	Reached engineering standards

3.3 Single coil field distribution

The coil is divided into two parts for computational reasons . The geometrical and electrical data are given earlier in Tables 3.1-1, 3.1-2 and 3.1-3. These data are real data taken after finishing the winding. Calculations performed by Siemens [6, 7] were done at an earlier stage of the project using ideal geometrical data. Therefore the comparison of values for magnetic field and inductances give some, but minor differences.

1st Example: Magnetic fields for single coil test at 15.96 kA

	SIEMENS	KfK
B_{ref}	7.77 T	7.61 T
B_{max}	9.02 T	8.84 T

The difference is only 2 % and is within the calculation accuracy taking into account the slightly different geometrical data used.

2nd Example: Inductance

SIEMENS	KfK
1.858 H	1.59 H

It should be mentioned that the calculation by Siemens was made at the end of 1979 [6] at a very early stage of LCT where the detailed geometry was not determined.. The measured value in TOSKA was 1.57 H [3] and the value calculated by KfK was 1.59 H. This discrepancy can easily be explained by the data of the geometry used for the coil at the time the Siemens calculations were performed.

Calculated values given in this report were attained using KfK computation architecture. Fig. 3.3-1 shows the reference point and the region where the maximum field occurs for single coil operation. This figure determines also the coordinate system of the coil. Fig. 3.3-2 shows the linear dependence of the magnetic field B vs coil current I. For B_{ref} this can be described by:

$$B_{ref} = 0.4757 \cdot I \; \{kA\} \quad T/kA$$

and for B_{max}

$$B_{max} = 0.5527 \cdot I \; \{kA\} \quad T/kA$$

B_{max} ist about 16 % higher than the field at the reference point.

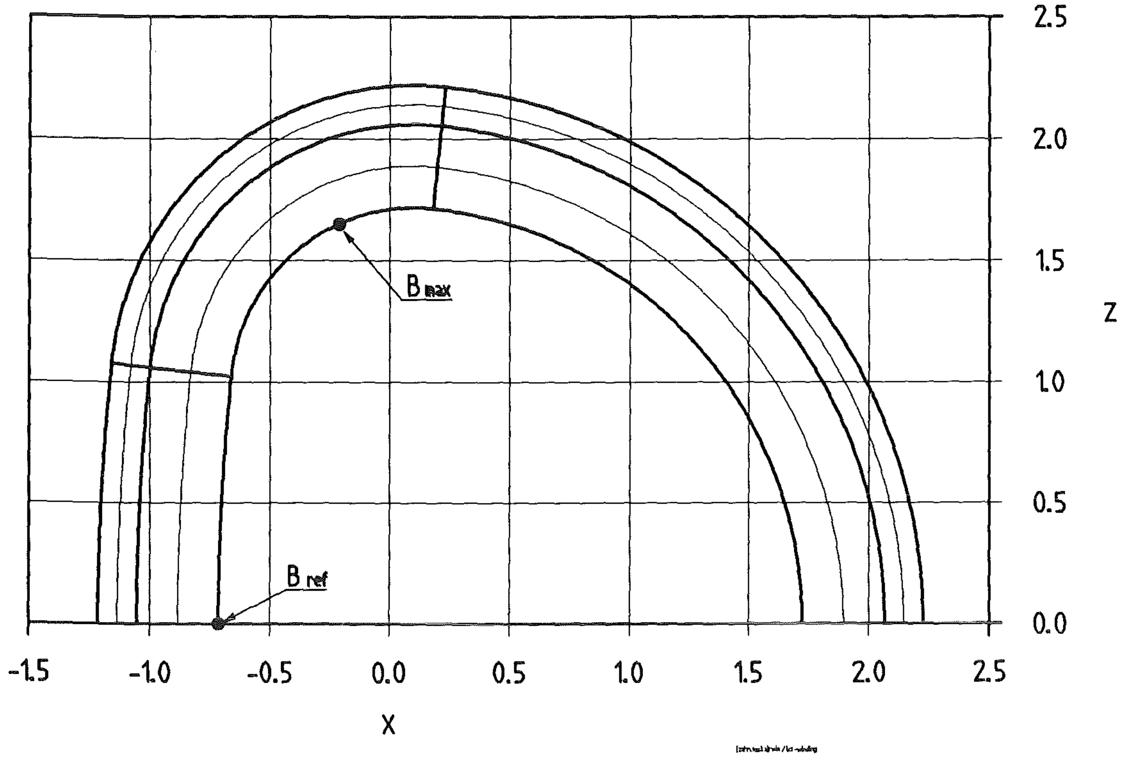

Fig. 3.3-1: Position of reference point for B_{ref} and point of maximum field B_{max} for the EURATOM LCT coil (local coordinate system).

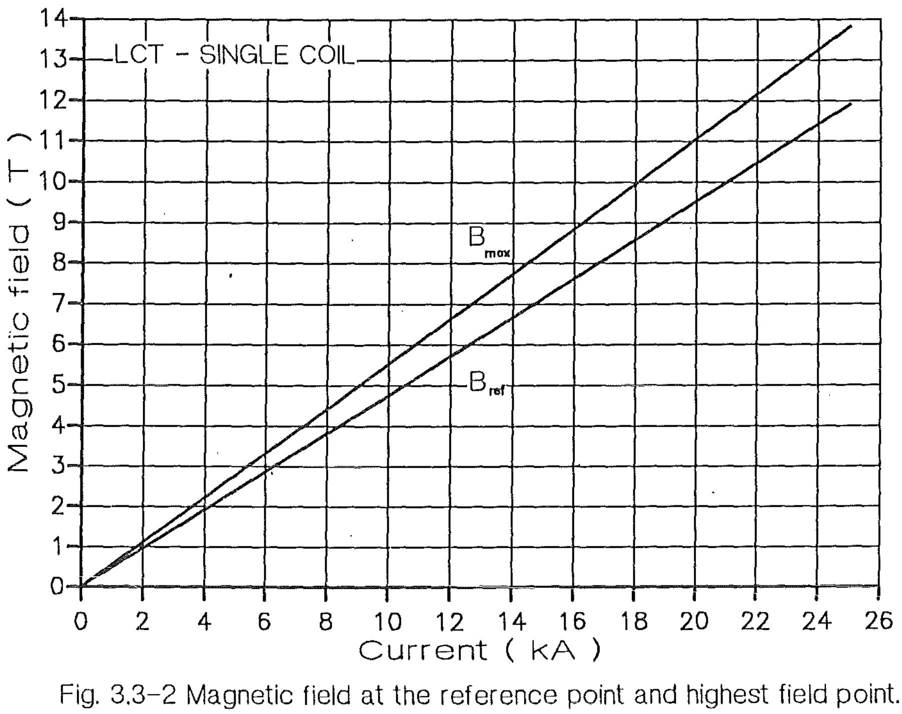

Fig. 3.3-2: Magnetic fields at the reference point and highest field point of the EURATOM LCT coil.

The field distribution of the EURATOM LCT coil is studied for two characteristic currents (or current densities):

- 16 kA, which is the current for extended-condition tests reached in Oak Ridge in single coil operation.
- 20 kA, the current envisaged for 1.8 K operation conditions.

An operational current in the range of 16 to 21 kA is foreseen for the TOSKA Twin test.

The results for 16 kA are presented in the following figures. The calculations are done in the global LCT coordinate system. Fig. 3.3-3 shows the B-contours in the midplane (X-Y) of the coil at z = 0 and Fig. 3.3-4 in the X-Y plane at z = 1.65 m, where the maximum field of the coil for single coil operation is located.

Fig. 3.3-5 shows the magnetic field B and its components B_x, B_y (B_z = 0 in the midplane) in dependence of x for y = -0.6 m. Fig. 3.3-6 shows the field and its components in the X-Y plane at z = 1.65 m and y = -0.6 m. It should be mentioned that the components are very different for both planes. The important component is B_y, and it is about 3 T for z = 0 and in a wide range of x values, but only about 2.5 T for z = 1.65 m and a smaller range of x values.

The results for higher currents are not presented here in figures because the field scales with current.

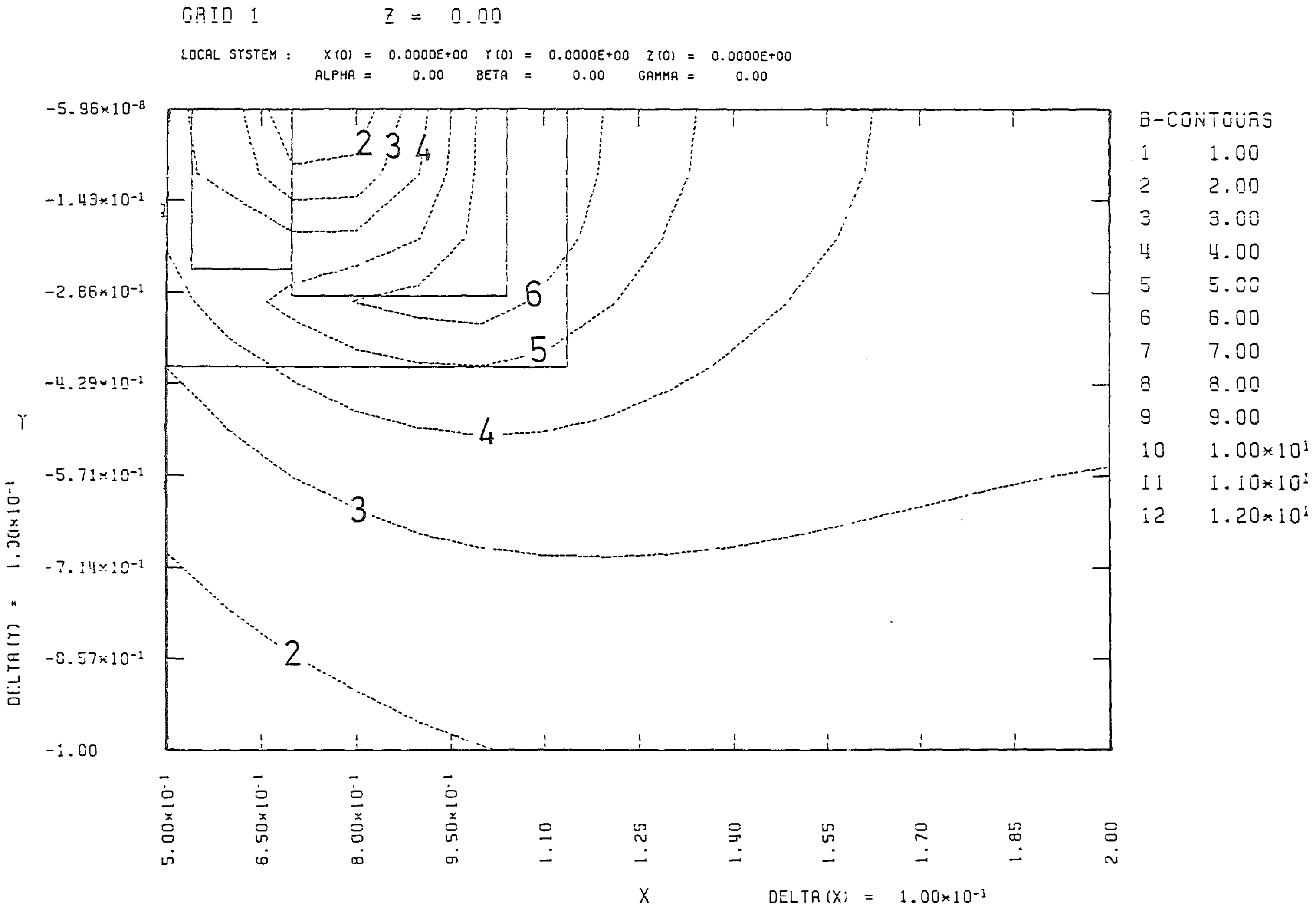

Fig. 3.3-3: B-contours in T for the Euratom LCT coil in the midplane (X-Y,z = 0) for 16 kA (x,y in m)

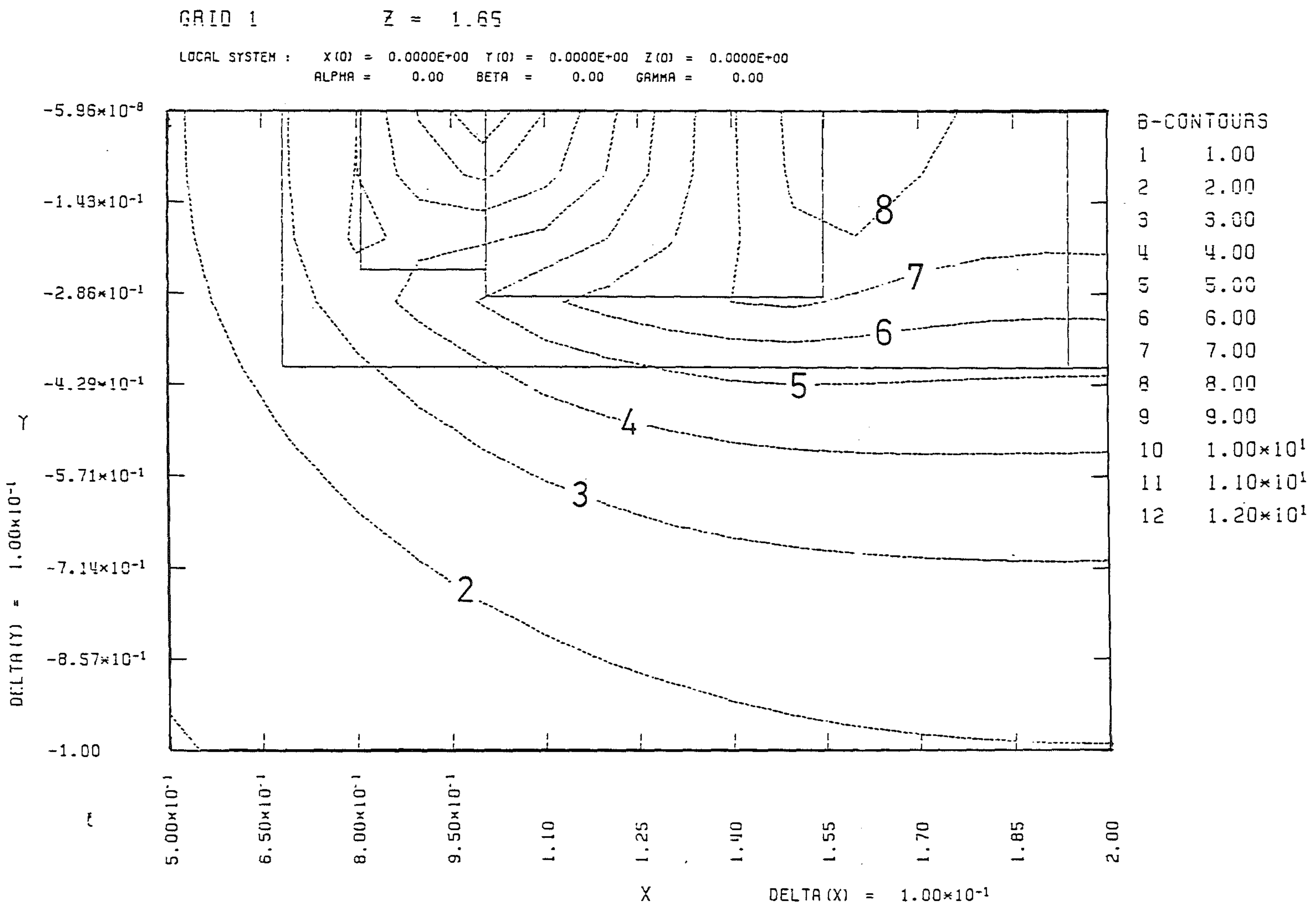

Fig. 3.3-4: B-contours in T for the Euratom LCT coil in the plane (X-Y at z = 1.65 m) for 16 kA (x,y in m)

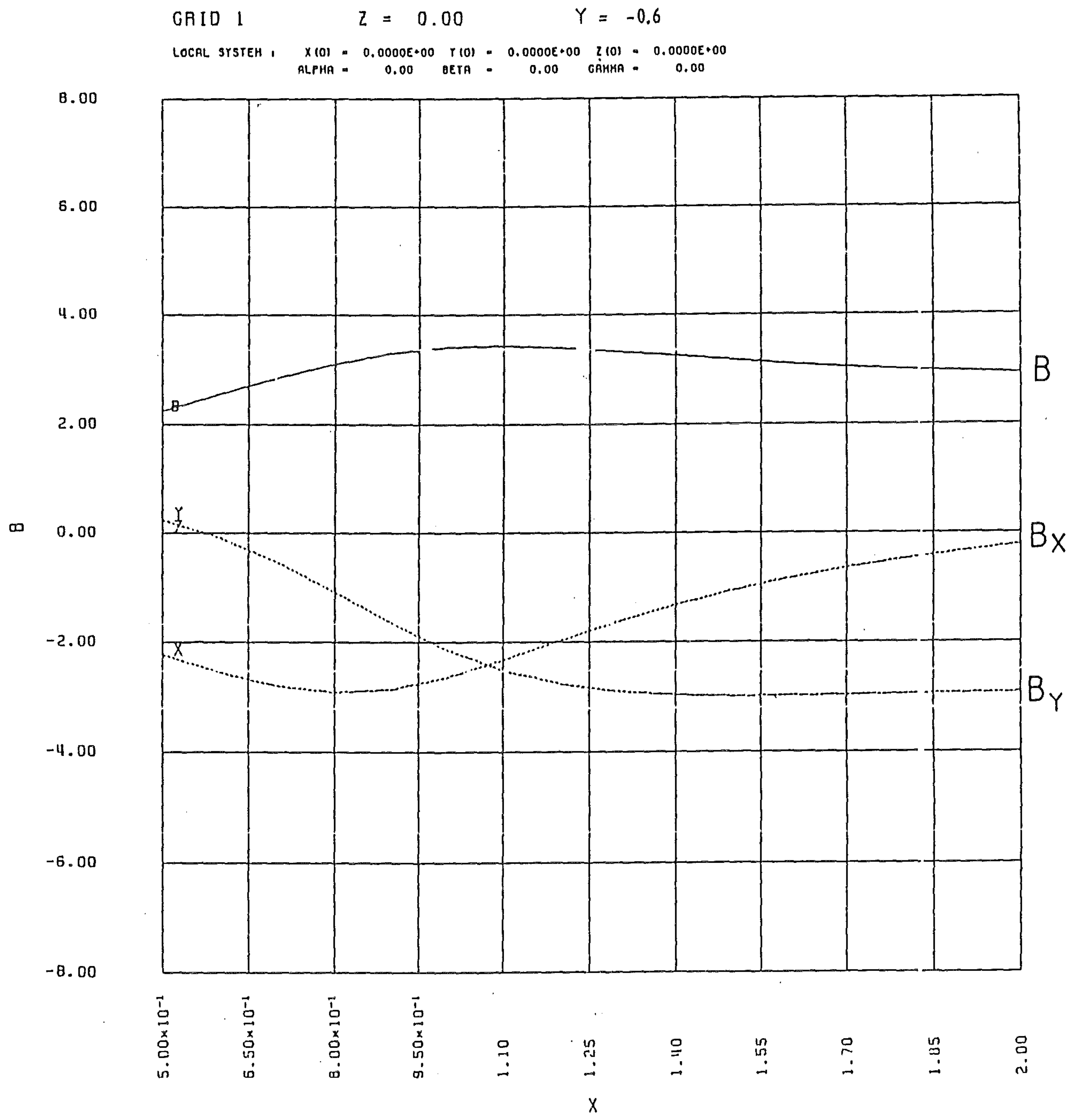

Fig. 3.3-5: Magnetic field and its components in the midplane of the coil in dependence of x for 16 kA (B in T, x in m).

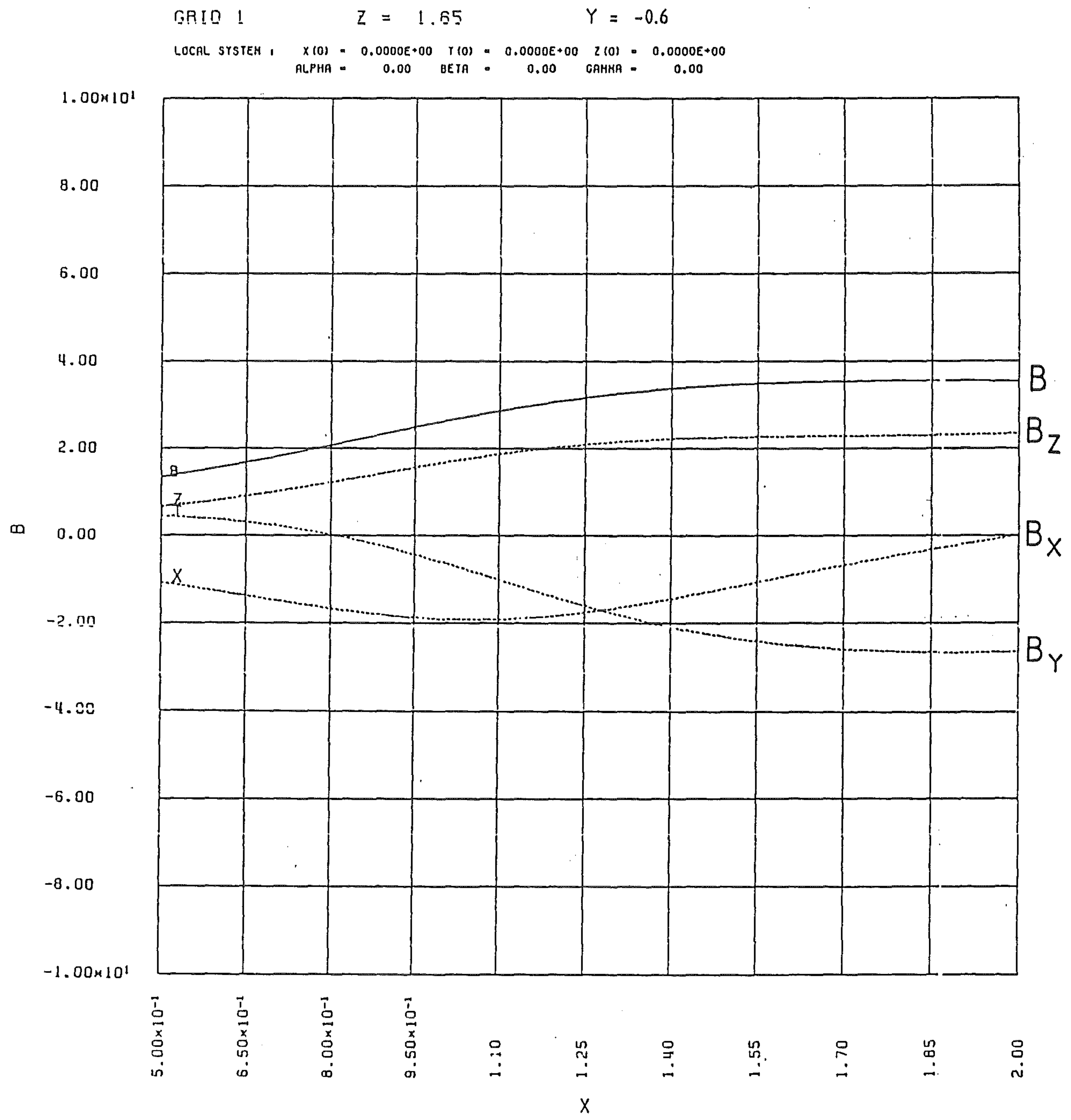

Fig. 3.3-6: Magnetic field and its components in the X-Y plane at z = 1.65 m in dependence of x for 16 kA (B in T, x in m).

Fig. 3.3-7 shows the field B and its component B_y ($B_x = 0$, $B_z = 0$) for z = 0 and y = 0 in dependence of x. Searching this figure small discontinuities in the plotted lines can be discovered. That is due to the value of the increment $\Delta x = 0.05$ m. If the increment gets smaller these effects disappear. The field inside the winding is linear and "bowl-like" in the bore of the magnet. At the bottom of the bowl the magnetic field is about 3.5 T to 4 T and about twice this value at the winding.

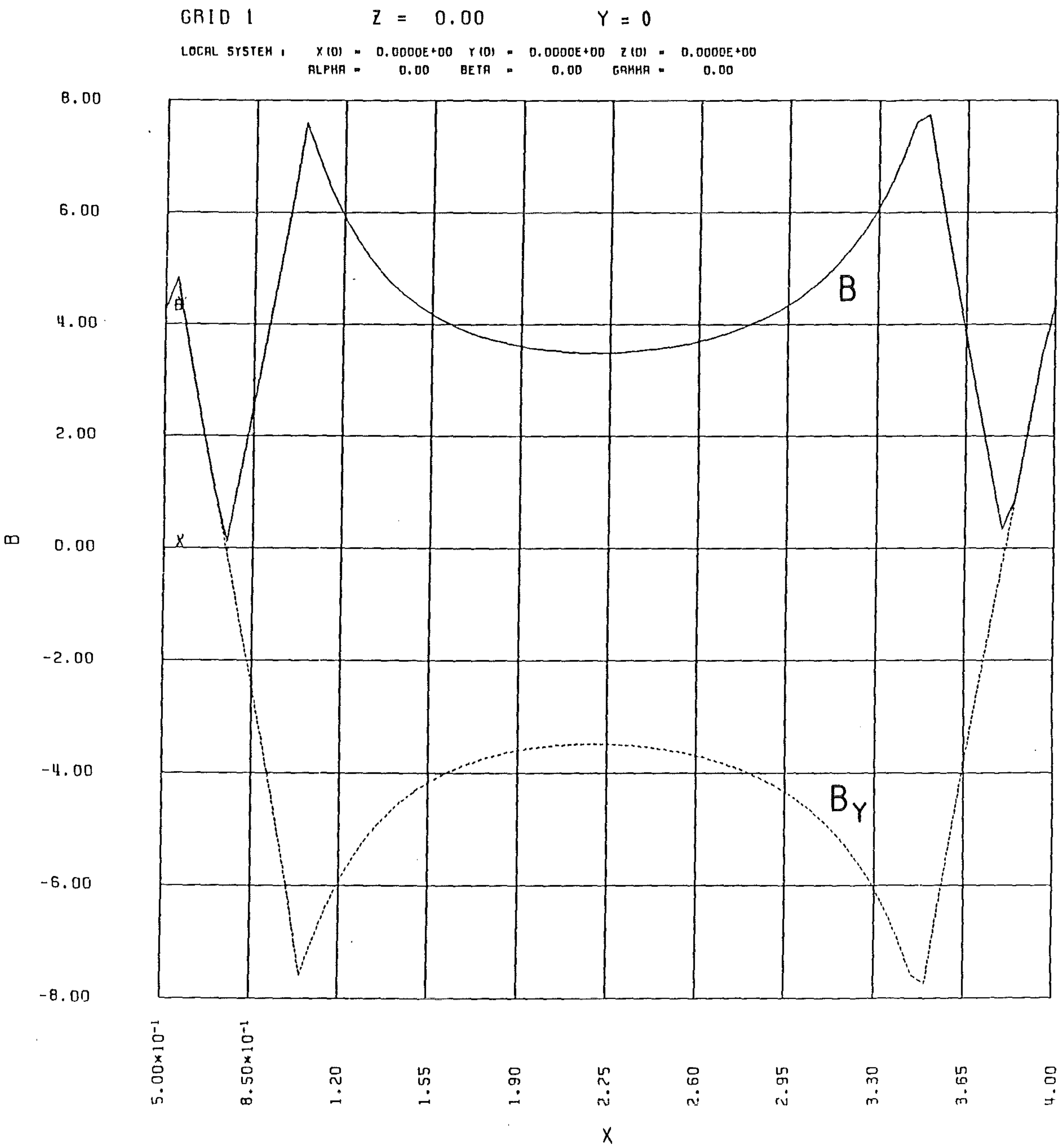

Fig. 3.3-7: Magnetic field B and B_y component of the EURATOM coil for z = 0 and y = 0 in dependence of x for 16 kA (B, B_y in T, x in m).

3.4 Expected performance of the EURATOM coil during the twin test

3.4.1 Introduction

The operational current of up to 21 kA at 1.8 K requires an examination whether the coil is able to sustain the loads occurring at this high current operation. The coil itself and different components of the coil were investigated with respect to the mechanical, electrical, thermal, and hydraulic behaviour. Two studies initiated by KfK were performed by Interatom in collaboration with Siemens [8,9]. One study dealt with the mechanical behaviour. In the other one the influence of the higher current (or field) on the operational behaviour of the coil and components eg current leads or diagnostic sensors was investigated. The results are summarized in the following subsections.

3.4.2 Mechanical behaviour

The same FE model was used for the stress analysis as for the TOSKA single coil calculations [7]. In order to balance the higher forces during a 21 kA operation the following cases were modelled in the FE-calculation:

A. Doubling of coil case thickness.
B. Holding the inner contour of the coil case.
C. Same as B, but with modification of the radial elasticity modulus of the coil within the straight section (from 2.7 GPa to 4.6 GPa).

The results of the numerical studies are:

- Doubling the thickness of the coil case according to A is not sufficient because the limits of the design stresses are exceeded, especially the given shear stress of 20 MPa is surpassed by a factor of 2.9 within the winding pack. The maximum von Mises stress of 512 MPa in the coil case surpasses the limit value of 500 MPa only by 2.4 %.

- The holding of the inner contour of the coil case according to B leads to a maximum von Mises stress of 283 MPa in the coil case distinctly below the given value of 500 MPa. However the shear stress is 38 MPa or 1.9 times higher than the given value of 20 MPa.

- By changing the radial elasticity modulus according to C the maximum shear stress drops to 32 MPa, but this is a local value, occurring only in a small portion of the coil volume.

The experimental investigation and the assessment of shear stress measurements led to the conclusion that the used shear stress samples for the LCT coil insulation system gave too low shear stress values. This was also shown by finite element calculations for the samples. The comparison of stress results from bending beam and lap shear measurements led to the conclusion that the first method gave the more realistic results. From this point of view a shear stress level of 50 MPa can be allowed. A final rating has to be made after calculations with an improved FE model including reinforcement of the coil, support structure and realistic boundary conditions.

3.4.3 Operational behaviour and quench influence

The results of the study assume the validity of the following statement:
By means of a suited mechanical support system of the magnet it must be assured, that all the hitherto valid values for mechanical stresses and resultant global displacements are not surpassed neither within the winding pack nor within the case.

A very important load case is a quench at 20 kA with a stored energy of almost 320 MJ. Therefore this case was given special attention. Several very different cases were investigated:

- a cooling channel of 252 m length becomes completely normal conducting,
- a piece of 3 m length in the middle of a cooling channel becomes normal conducting,
- a piece of 3 m length at the inlet becomes normal conducting, and
- an observed quench with 6 m normal conducting zone at the inlet at T = 3.75 K and 13.8 kA.

The results show a very different behaviour. A very high pressure level of 17 MPa (170 bar) occurs only at a sudden transition of a total cooling length of 252 m to normal conductivity. However, the likelihood of such an event is extremly low. The maximum pressure at a quench of short lengths (3 m) is mainly determined by the relief valves at the inlet and outlet. The time behaviour of temperature and

He-velocity depends essentially on the conditions at both ends determined by the He supply system. A comparison of calculated and measured pressure increase with conditions used in the tests [10] is shown in Fig. 3.4-1. The measured pressure increase was much lower and slower than the calculated one which could be explained by the volume of the piping system including ventlines acting as buffer.

During a 20 kA quench of the LCT coil an amount of energy per unit volume of 1.67 MJ/m^3 is transferred to the coil case and produces a maximum temperature of about 27 K in the coil case without energy exchange with the neighbourhood. The temperature within the winding does not exceed 70 K. Therefore a quench at 20 kA should probably not harm the coil.

Components within the inlet and outlet region were tested up to 2.5 MPa (25 bar) and should therefore sustain a 20 kA quench. The insulation system was tested up to 12 kV. No increase of the dump voltage is necessary. It will remain at 2.5 kV for high current operation too. The current carrying and cooling capacities of the current lead feedthroughs are sufficient. The forces can be balanced and therefore the current lead feedthroughs can be used without any change.

The average magnetic field at the conductor joints is about 1 T during the 20 kA single coil test and the resistance of the joints is 0.29 nΩ. The power loss is 0.116 W for one joint and 1.508 W for the 13 existing joints which is not prohibitive for the operation of the magnet at 20 kA.

The sensors of the magnet were originally designed for an operation at 3.5 K and up to 9 T. The temperature sensors are calibrated in the range from 2 to 100 K. An extension to 1.8 K and up to 12 T should be easily possible with some extrapolation or even by an exchange of some sensors.

If the case and the winding pack are cooled down and operated at different temperatures (case at 4.2 K up to 5 K, supercritical He; winding pack at 1.8 K up to 3.4 K), then a heat flow exists from the case towards the winding. A very pessimistic estimate gives 330 W, where the heat transfer coefficient for the steel bladders filled with epoxy resin is the great unknown quantity. An experimental determination in Oak Ridge gives k = 0.13 W/m^2 between 4 K and 15 K. Using this value the resultant heat input to the coil winding is 8.7 W.

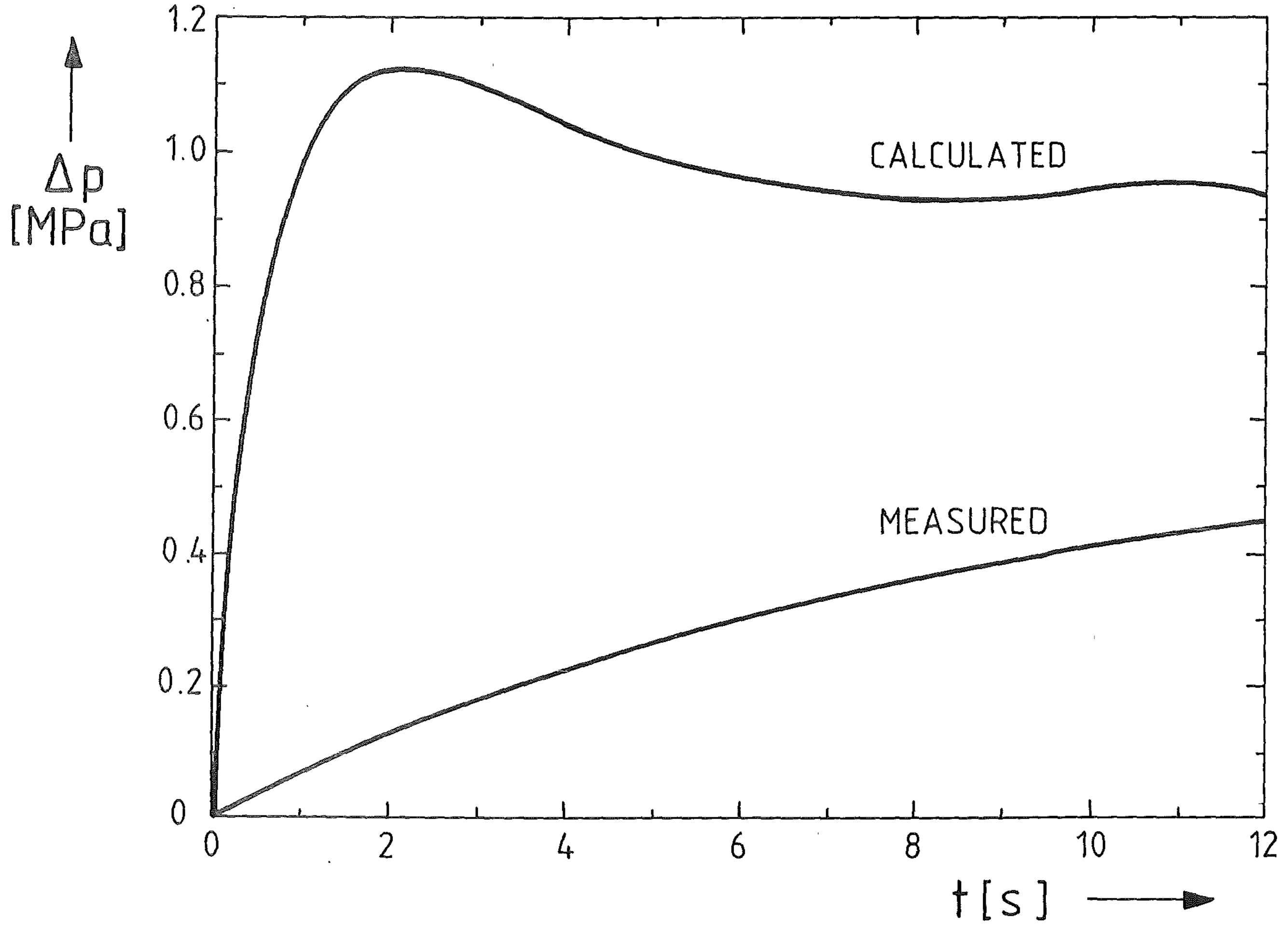

Fig. 3.4-1: Measured and calculated pressure drop values for a quench with 6 m normal conducting zone at the inlet at T = 3.75 K and 13.8 kA.

At the current lead feedthroughs the convection of He has to be avoided. The pipes within the He supply header have to have additional thermal insulation against the case. The estimated losses are in the order of 25 W.

As a conclusion, the operation of the EURATOM LCT coil at 1.8 K and up to 20 kA is possible if a suitable support system for the coil is constructed keeping strain and stress values within the allowed limits.

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Band A: Entwurf, Versuche, Planung*
Band B: Berechnungen.*

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[10] A. Hofmann, P. Komarek, A. Maurer, W. Maurer, G. Ries, B. Rzezonka, H. Salzburger, Ch. Schnapper, A. Ulbricht, G. Zahn, Further Use of the Euratom LCT Coil, 15th Symposium on Fusion Technology, Utrecht, Netherland, September 19-23, 1988.

* unpublished

4. TOSKA Twin test facility

4.1 Basic considerations

The test arrangement discussed here is called TOSKA Twin because there are only two inseparable coils within the TOSKA cryostat. The first one is the EURATOM LCT coil delivering the magnetic background field, the second one is the NET model coil which is aimed to set up the field to the required test value. The latter one can be composed by pancakes out of different TF-conductors.

The performance of the EURATOM LCT coil is described in the previous chapter. It is shown (see Fig. 3.3-3) that near the winding and/or case within the bore of the LCT magnet a background field of 5 T to 6 T is produced for 16 kA operational current. Beside the coil a field of 3 to 4 T is produced in a region accessible for testing of NET model coils. Both field regions will be investigated whether they are suited for NET model coil testing.
The LCT coil current is chosen to be 16 kA already reached in Oak Ridge in a single coil test. A current enhancement is envisaged, but this requires a reinforcement of the coil structure. 18 kA seems to be a good choice and rises the field contribution of the LCT coil by 12.5 % while keeping the expense for the reinforcement in acceptable limits, but an 1.8 K operation is required. This question is addressed in following chapters.
With respect to the model coils to be tested one representative coil was chosen i.e. one representative current density. This simplifies the design calculations because only one model coil has to be handled.

Searching through the data of TF conductors in [1, 11] it is found that the current densities of the ECN and KfK conductors are nearly the same (2410 A/cm^2, resp. 2406 A/cm^2). The current density of the SIN (now PSI) conductor is about 10 % lower (2180 A/cm^2). The current density of the proposed cable in conduit conductor for the central solenoids (2435 A/cm^2) is by chance nearly the same as for the ECN and KfK conductors. For design purposes the current density and geometrical data of the KfK conductor were arbitrarily chosen. So the rated current density at 16 kA for the NET model coil is 2406 A/cm^2 and is 3308 A/cm^2 at a current of 22 kA. The conductor dimensions are 38 mm x 17,5 mm (axial width times radial thickness), including 0.5 mm insulation. These conductor dimensions were kept during the calculations despite minor changes in the conductor design.

4.2 TOSKA Twin test with an adjacent NET model coil

The design of this test arrangement commenced with the original Cluster Test Configuration C 6 (see Fig. 3.5-2 of [1]). At first the CH coil was not used. Then the case of the EURATOM LCT coil was enlarged. The thickness was set to be 10 cm instead of 5 cm as it is now in order to take into account some reinforcement for the calculations or some space which is occupied by sensors sitting on the coil case. The model coils were surrounded by a case of 5 cm thickness which is an arbitrary choice at this time. Fig. 4.2-1 shows the arrangement after performing these steps, having two different NET model coils. Then the transition to one representative current density was done. If the NET model coil is adjacent (or beside) the EURATOM LCT coil, the configuration is called Adjacent Twin Configuration (ATC).

The following parameters were varied during the design:
- the distance between the coils in the x-direction (according to Fig. 4.2-1),
- the distance between the coils in the y-direction,
- the rotation angle,
- the current density in the LCT coil (to some extent),
- the number of pancakes of the NET model coil,
- the number of layers per pancake of the NET model coil.

The minimum bending radius of 1 m for the NET model coils was kept. The influence on the magnetic field at the reference point in the midplane can be described as follows:
- If the coils are parallel (rotation angle = 0°), then the enhancement of the distance in y-direction leads naturally to a decrease of the magnetic field at the reference point.
- If the coils are parallel and the distance of the coils (y-direction) is constant, then a variation of the x-position of the model coil with respect to the LCT coil leads to a maximum of the reference field within a wide range of x-values.
- If a parallel x-y-position is fixed and the coils are rotated relative to each other then the field at the model coil reference point rises slowly with rising rotation angle. This is due to the vector character of the magnetic field.

Detailed analysis of the available and acceptable parameter range led to the definition of a reference case for the TOSKA Twin NET model coil test. Fig. 4.2-2 shows the midplane of the arrangement. The main characteristics of this reference case are given in Table 4.2-1. Table 4.2-2 contains the data of the NET model coil to be tested.

It should be mentioned that B_{ref} is always taken in the midplane of the coil system (X-Y plane at z = 0). The maximum field point differs generally from the reference point and is not necessarily at the location shown in Fig. 3.3-1. That figure shows the maximum field point for the single coil; if there is a model coil, then the maximum field point can migrate to other locations at the winding.

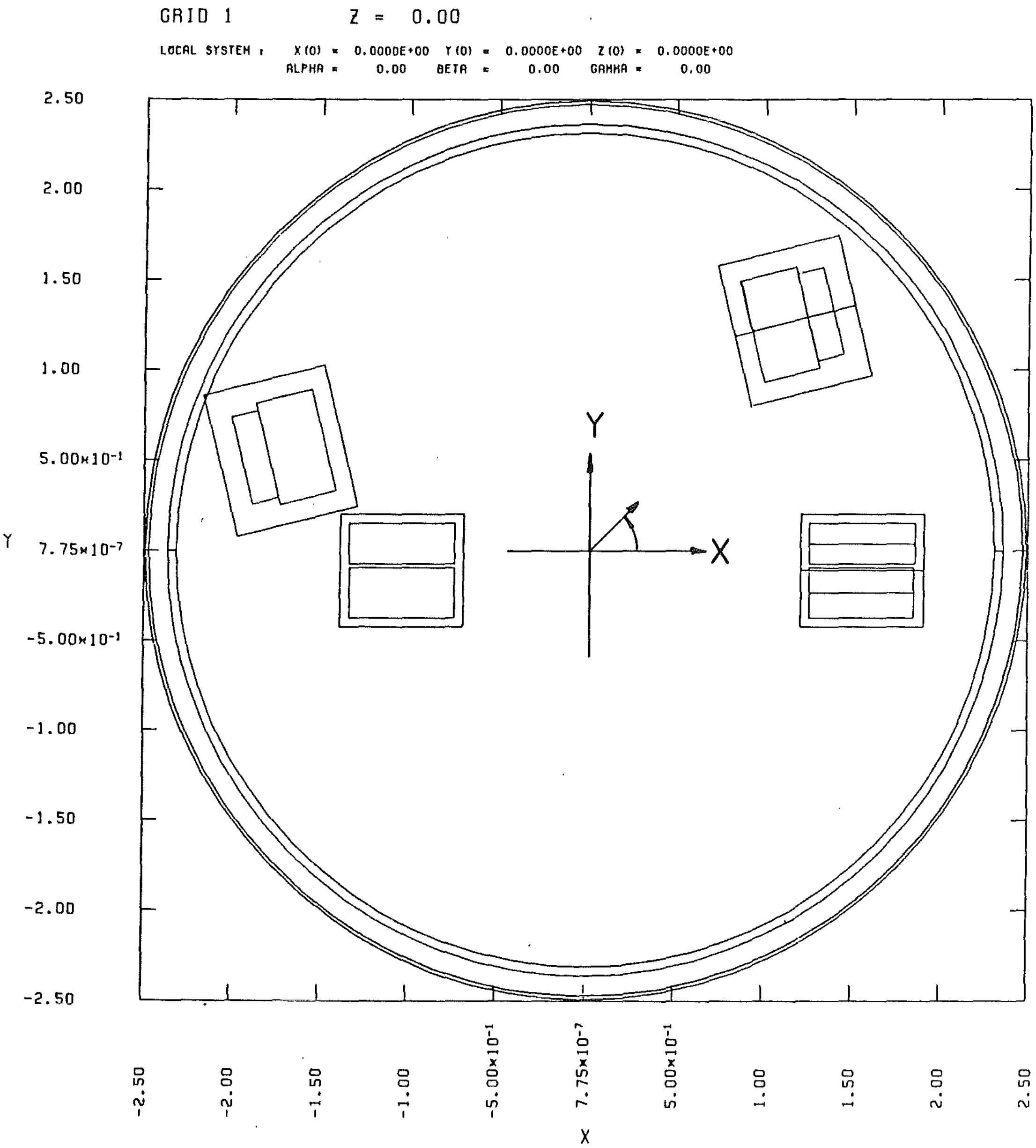

Fig. 4.2-1: The original Cluster Test Configuration without the Swiss Coil and with enlarged case thickness of the EURATOM LCT Coil. Also the coordinate system used for calculation purposes is defined. (x, y in m).

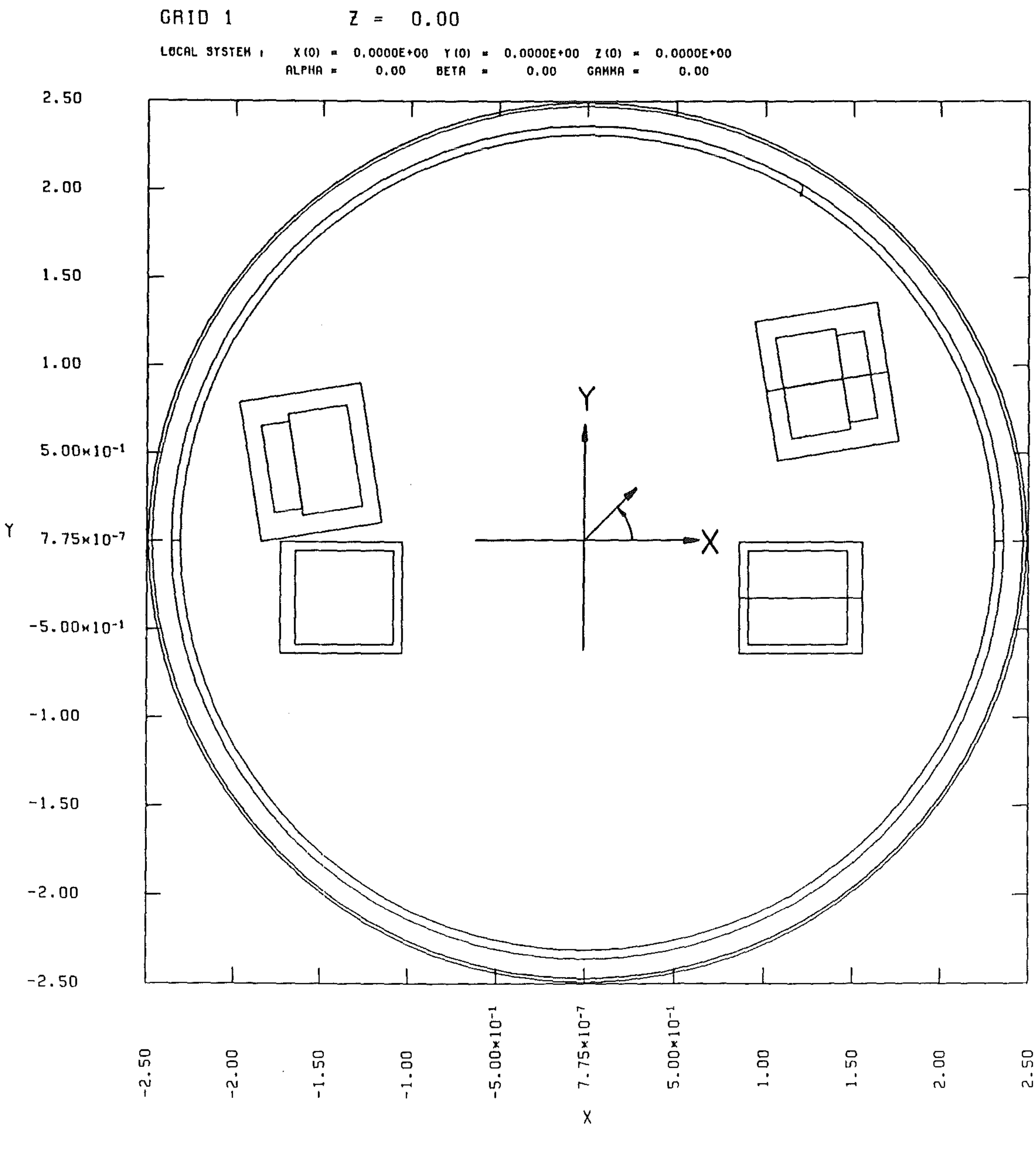

Fig. 4.2-2: Arrangement of TOSKA ATC (x, y in m).

Table 4.2-1: Main characteristics of the TOSKA ATC

	Unit	NET Model Coil		EURATOM LCT Coil
Operation temperature	K	3.5		1.8
Conductor current Total coil current	kA MA	22 9.856		18 10.584
B_{ref}	T	11.69		10.33
B_{max}	T	11.85		10.33
Force in x-direction (centering force) Force in y-direction (out-of-plane force)	MN MN	-18.5 115.2		18.5 -115.2
Stored self-energy	MJ	138		253
Total stored energy	MJ	507		
Relative rotation angle	degree	9		
Case thickness	mm	25	50	50
Hoop stress	MPa	210	170	x
Axial pressure	MPa	-48	-52	x
Radial pressure	MPa	-62	-82	x
Shear stress	MPa	-14	-11	x

x has to be investigated together with the reinforcement of the EU-coil.

Table 4.2-2: Characteristics for ATC

Winding pack characteristics	Unit	NET Model Coil
X-position of coil center Y-position of coil center	m m	0.0 -0.32
Current Current density	kA kA/cm^2	22 3.308
Kind of winding		double pancake winding
Number of pancakes Number of layers per pancake Total number of turns		7 x 2 32 448
Inner radius, r_i Radial winding thickness Axial winding width Average winding radius	m m m m	1.00 0.56 0.532 1.28
Average turn length Average conductor length per pancake (= cooling length)	m m	8.05 258.
Total conductor length (not including spare lengths for fabrication and joints (about 10 %))	m	3603.
Winding cross section Winding volume Estimated winding weight (ρ about 7 t/m^3)	m x m m^3 t	0.298 2.396 16.8
Total coil current Ampere-meter	10^6 A 10^6 Am	9.856 79.34
Stored self energy B_{ref} B_{max} Temperature	MJ T T K	138 11.69 11.85 3.5

Fig. 4.2-3 shows the field in the region of the reference points of the coils.
Fig. 4.2-4 shows the loadline for the EURATOM LCT coil in ATC and Fig. 4.2-5 shows that for the NET model coil.

The inductance matrix is given in the following Table 4.2-3.

Table 4.2-3: Inductance matrix of the ATC. (EFFI calculates the single turn inductance, i.e. inductance in H divided by the product of the turn numbers N_p and N_q. In case of self inductance p = q)

$\times 10^{-6} N_p N_q$	EU-LCT-Coil		NET MODEL
	IN-LCT	OUT-LCT	
IN - LCT	4.521	4.160	1.096
OUT - LCT	4.160	6.369	1.142
NET MODEL	1.096	1.142	2.836

In order to calculate stored energies the turn numbers and the currents has to be added. The turn number for IN-LCT is 420, for OUT-LCT 168, and for the NET model coil 448. The current for the LCT coil is 18 kA and 22 kA for the NET model coil.

The total stored energy of the test configuration can be written as

$$
\begin{aligned}
E_{total} &= E_{LCT} + 2 \cdot E_{coupling} + E_{Model} \\
&= (253 + 116 + 138)\ \mathrm{MJ} \\
&= 507\ \mathrm{MJ}
\end{aligned}
$$

116 MJ coupling energy corresponds to about 23 % of the total stored energy. Therefore special attention has to be credited to the layout of the coil protection system as already discussed in [1]. Especially the availability of suitable circuits for energy removal at this current level has to be investigated.

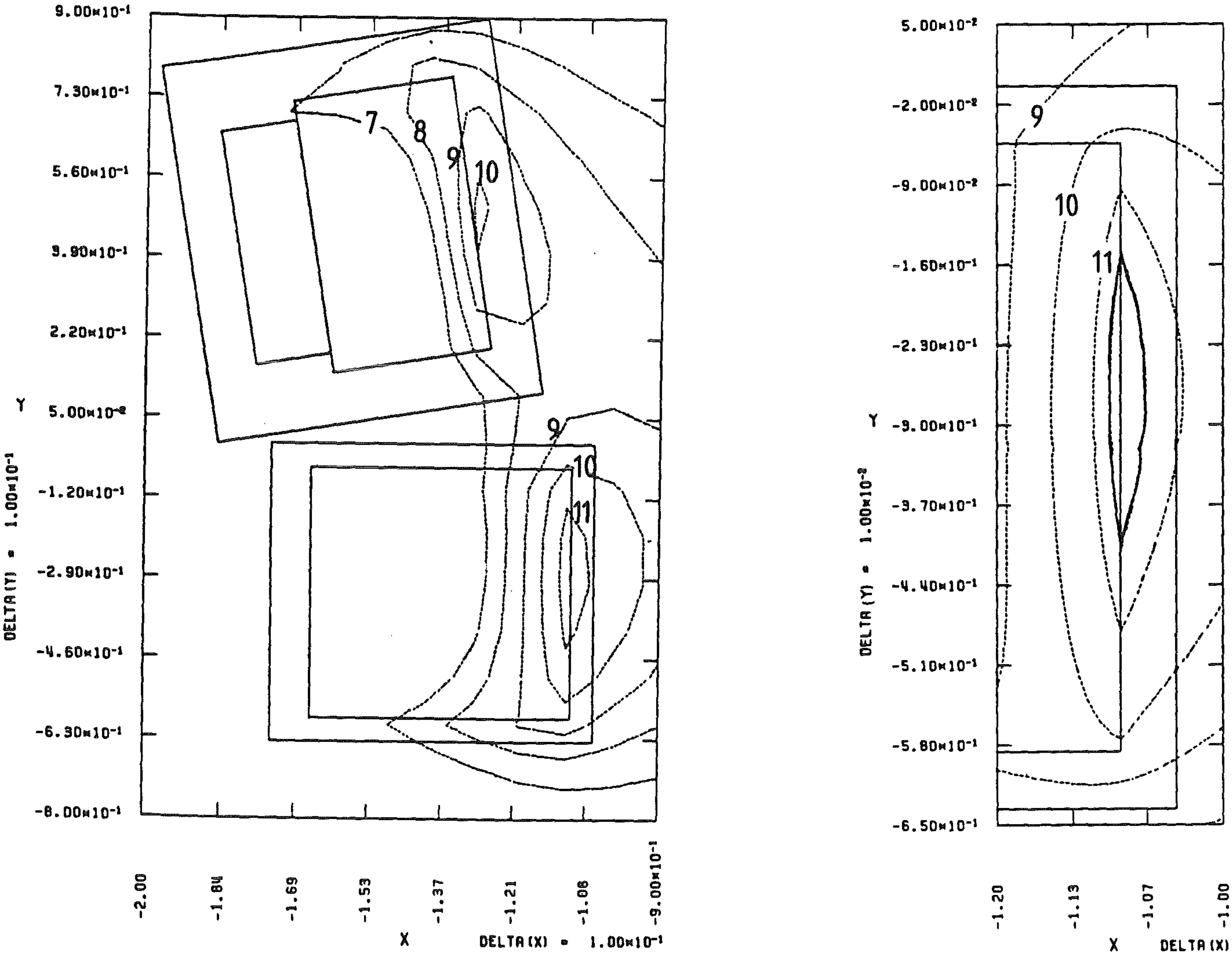

Fig. 4.2-3: Magnetic field in the region of the reference points of the coils. (Left for both coils, right for NET model coil only). (x, y in m).

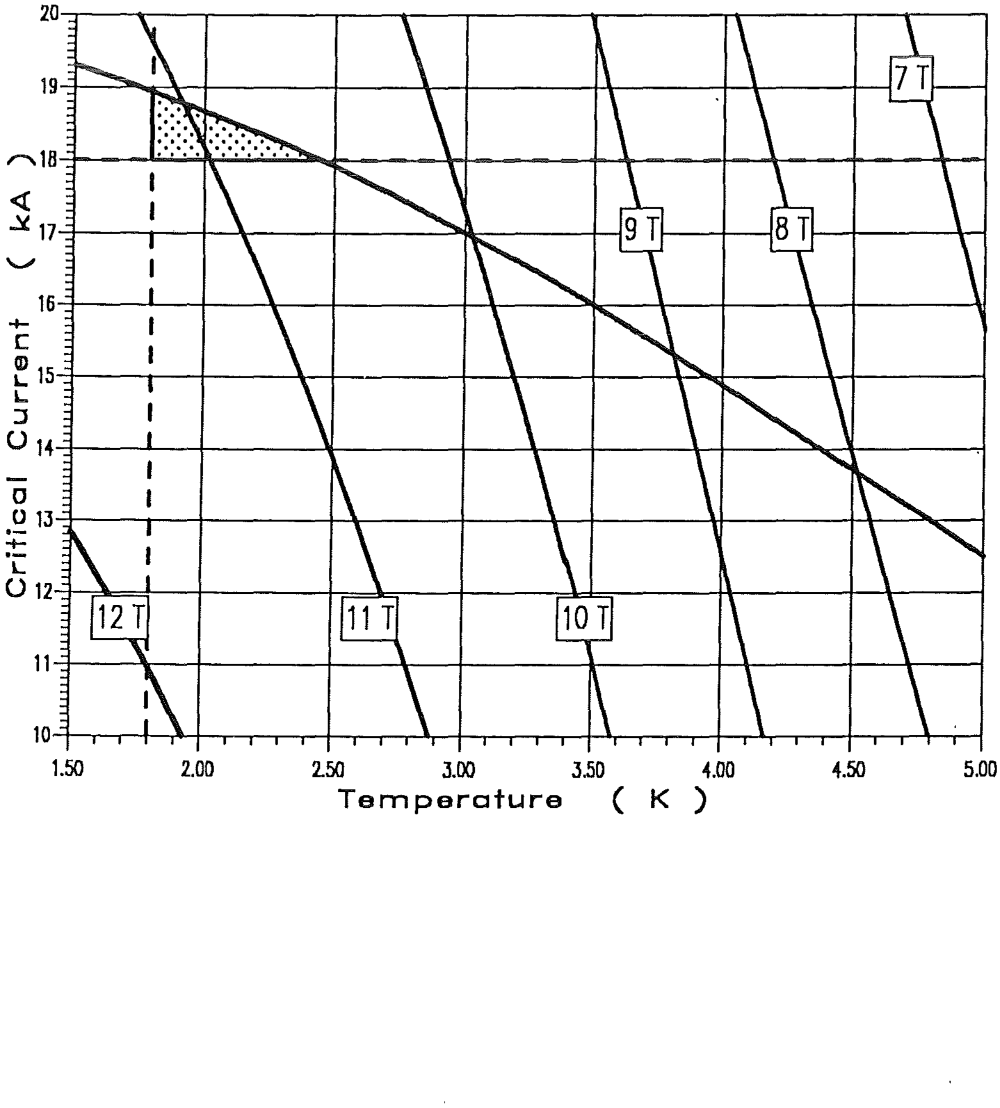

Fig. 4.2-4: Current sharing line for the EU-LCT coil in ATC.

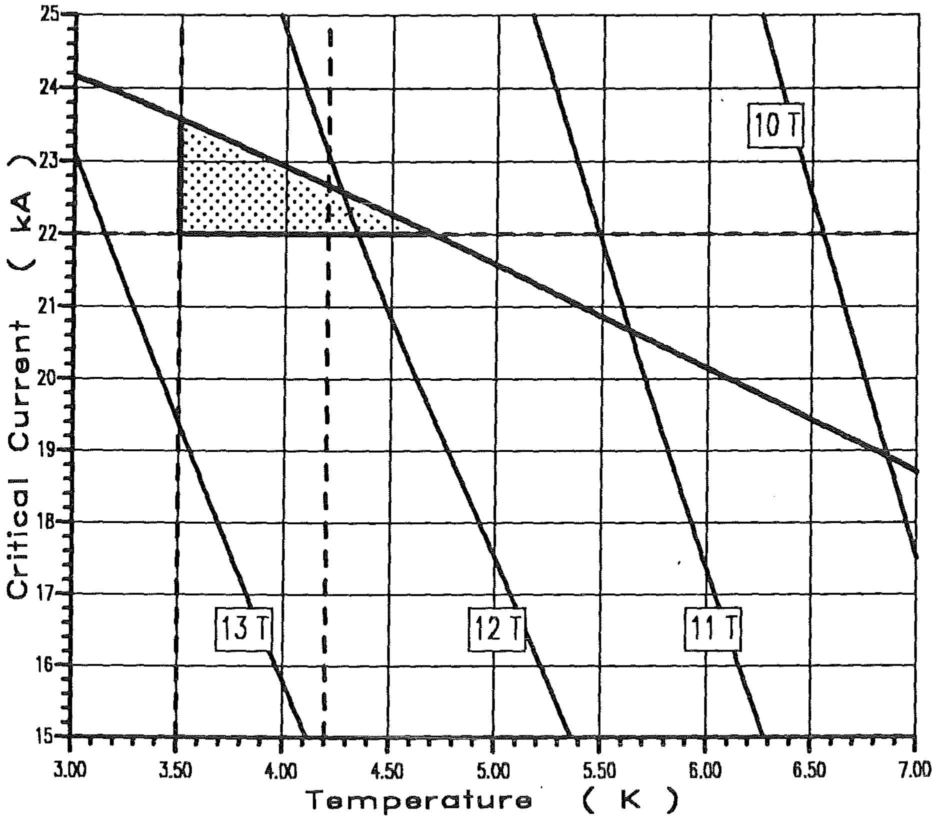

Fig. 4.2-5: Current sharing line of the NET model coil in ATC.

4.3 NET model coil as insertion of the LCT coil

4.3.1 Investigation of an arrangement with inserted upright model coil

Considering the higher magnetic field within the bore of the EURATOM LCT coil as background field for conductor, pancake, and model coil tests (compared to fields beside the coil) it was investigated whether it is possible to test NET model coils inside the bore. The result and consequences of this investigation are outlined. This configuration where the NET model coil is inserted into the bore of the EURATOM LCT coil, is called Inserted Twin Configuration (ITC).

Studying the field within the bore of the LCT coil and requiring that the LCT coil should provide a background field of about 5 T a the minimum inner winding diameter (2 r_i) is found to be 1.9 m and a maximum winding thickness of 0.15 m is the result. Using the KfK conductor dimensions one gets 8 layers (radial) per pancake. The number of pancakes (axial) is to some extent a free parameter. The arrangement of the coils is shown in Fig. 4.3-1.

The result of a parameter study is summarized in Table 4.3-1. Some conclusions can be drawn:

- An enhancement of the number of pancakes above 14 has only a very small influence on the midplane field at the model coil winding.
- The reduction of the minimum bending radius to 0.81 m or the enhancement of the winding thickness or number of layers is the way to reach more than 10 T.
- A bending radius of 0.81 m leads to 0.27 % bending strain for the superconductor and to 1.02 % for the stainless steel of the conductor jacket.
- Whether a minimum bending radius of 0.81 m is acceptable or not has to be decided in view of the relevance of the test for NET.

A current of 16 kA in the EURATOM LCT coil was used for this first investigations. An enhancement of the current of the LCT coil is necessary to reach a higher contribution to the field. The field contribution of the LCT coil at the reference point is 4.5 T for 16 kA. If 18 kA can be carried by the LCT coil, then the field at the reference point of the NET model coil will be 11.40 T and for 20 kA the field is 11.97 T. The maximum magnetic field occurs as shown in Fig. 4.3-1 in the same reference plane, but opposite to the reference point. It is 11.6 T for 18 kA and 12.17 T for 20 kA. Furtheron, 18 kA operational current in the LCT coil is used.

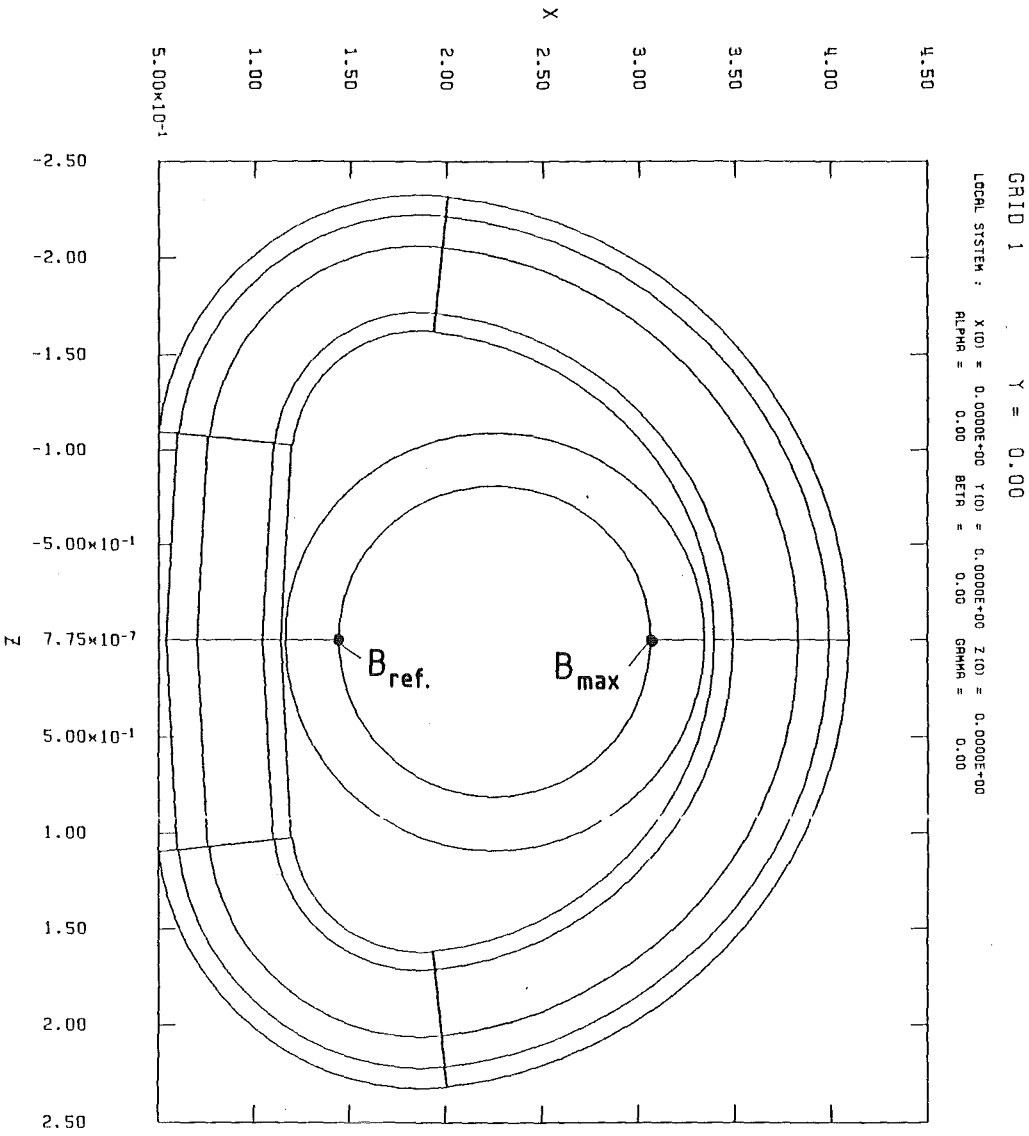

Fig. 4.3-1: Coil arrangement in ITC with model coil in upright position (x, z in m).

Table 4.3-1: Result of a parametric study of an inserted NET model coil. (The current in the LCT coil is 16 kA)

Inner Radius r_i [m]	Radial Thickness DR [m]	Axial Width DA [m]	Number of Pancakes	Number of Layers	B_{ref} [T]
0.95	0.14	0.532	14	8	8.4935
"	"	0.57	15	8	8.5661
"	"	0.76	20	8	8.8676
0.915	0.175	0.532	14	10	8.8076
0.81*	0.28	0.532	14	16	10.304
"	"	0.57	15	16	10.492
"	"	0.608	16	16	10.672

* The resulting strain ε for the superconductor is 0.27 % and for stainless steel jacket of the KfK conductor 1.02 %.

Table 4.3-2 contains the main characteristics of the test arrangement with a common coil center for both coils (y = 0). This implies zero out-of-plane forces. However, the x-position can't be freely chosen due to space reasons. Therefore a finite centering force occurs. The properties of the NET model coil are summarized in Table 4.3-3.

Fig. 4.3-2 shows the B-contours for the coil arrangement and also a very attractive feature of this arrangement. The field at the LCT coil will be partly cancelled in the high field region and therefore the safety margin of the LCT coil rises if the model coil is energized. Fig. 4.3-3 shows this behaviour. The highest field of the LCT coil occurs at the corners of the coil. This is typical for this special configuration.

Also the out-of-plane load will be low and can be chosen by choosing the proper displacement of the NET model coil in y-direction from the common center of both coils. In any case the out-of-plane force will not reach 26.6 MN already reached in the LCT test if the test coil stays fully or partly within the bore of the LCT coil. For example the out-of-plane load will reach 17.65 MN in case of a displacement of 15 cm in y-direction from the common coil center (y = 0).

This arrangement has a very attractive advantage since the conductor length is only 1.6 km, i.e. only half of the length needed for a test configuration with a test coil beside the EURATOM LCT coil. However, there is the caveat of the minimum bending radius of only 0.81 m. With respect to installation this ideal coil arrangement has the disadvantage that all supply lines (current, coolant, diagnostic) have to be connected in the space between model coil and EURATOM LCT coil within the bore or at the side of the model coil. Fig. 4.3-4 shows a possible solution but the space for feedthrough and joint is limited. In the next subsection a modified solution will be presented.

The loadline for the EURATOM LCT coil in ITC with model coils in upright position is shown in Fig. 4.3-5. At an operation of 1.8 K and 18 kA a sufficient safety margin is available not only for the temperature (1.4 K), but also for the current (2.7 kA or 15 %). Fig. 4.3-6 shows the loadline for the inserted NET model coils in ITC. Here is the safety margin for the temperature (1.3 K) about the same as for the LCT coil, but the current margin is only 1.8 kA (or about 8.2 %). It should be noted that this loadline is also valid for the configuration of an inserted model coil with a 60° slope which is discussed next.

Table 4.3-2: Main characteristics of the TOSKA ITC with the NET model coil in an upright position

	Unit	NET Model Coil	EURATOM LCT Coil
Operation temperature	K	3.5	1.8
Conductor current Total coil current	kA MA	22 5.632	18 10.584
B_{ref}	T	11.4	8.0
B_{max}	T	11.6	9.64
Force in x-direction (centering force) Force in y-direction (out-of-plane force) Force in z-direction	MN MN MN	3.72 0.0 0.0	- 3.72 0.0 0.0
Stored self-energy	MJ	32	253.4
Total stored energy	MJ	356.4	
Case thickness	mm	50	50
Hoop stresses	MPa	166	x
Axial pressure	MPa	70	x
Radial pressure	MPa	95	x
Shear stresses	MPa	9	x

x has to be investigated together with the reinforcement of the EU-coil.

Table 4.3-3: Characteristics of the ITC. Model coil upright in the EU LCT coil.

Winding pack characteristics	Unit	Upright NET model coil
X-position of coil center Y-position of coil center	m m	0.0 variable, not yet determined
Current Current density	kA kA/cm^2	22 3.308
Kind of winding		double pancake winding
Number of pancakes Number of layers per pancake Total number of turns		8 x 2 16 256
Inner radius, r_i Radial winding thickness Axial winding width Average winding radius	m m m m	0.81 0.28 0.608 0.95
Average turn length Average conductor length per pancake (= cooling length)	m m	5.97 95.5
Total conductor length (not including spare lengths for fabrication and joints (about 10 %))	m	1528.
Winding cross section Winding volume Estimated winding weight (ρ about 7 t/m^3)	m x m m^3 t	0.17 1.02 7.
Total coil current Ampere-meter	10^6 A 10^6 AM	5.632 33.62
Stored self energy B_{ref} (for 18 kA in LCT coil) B_{max} (for 18 kA in LCT coil) Temperature	MJ T T K	32 11.4 11.6 3.5

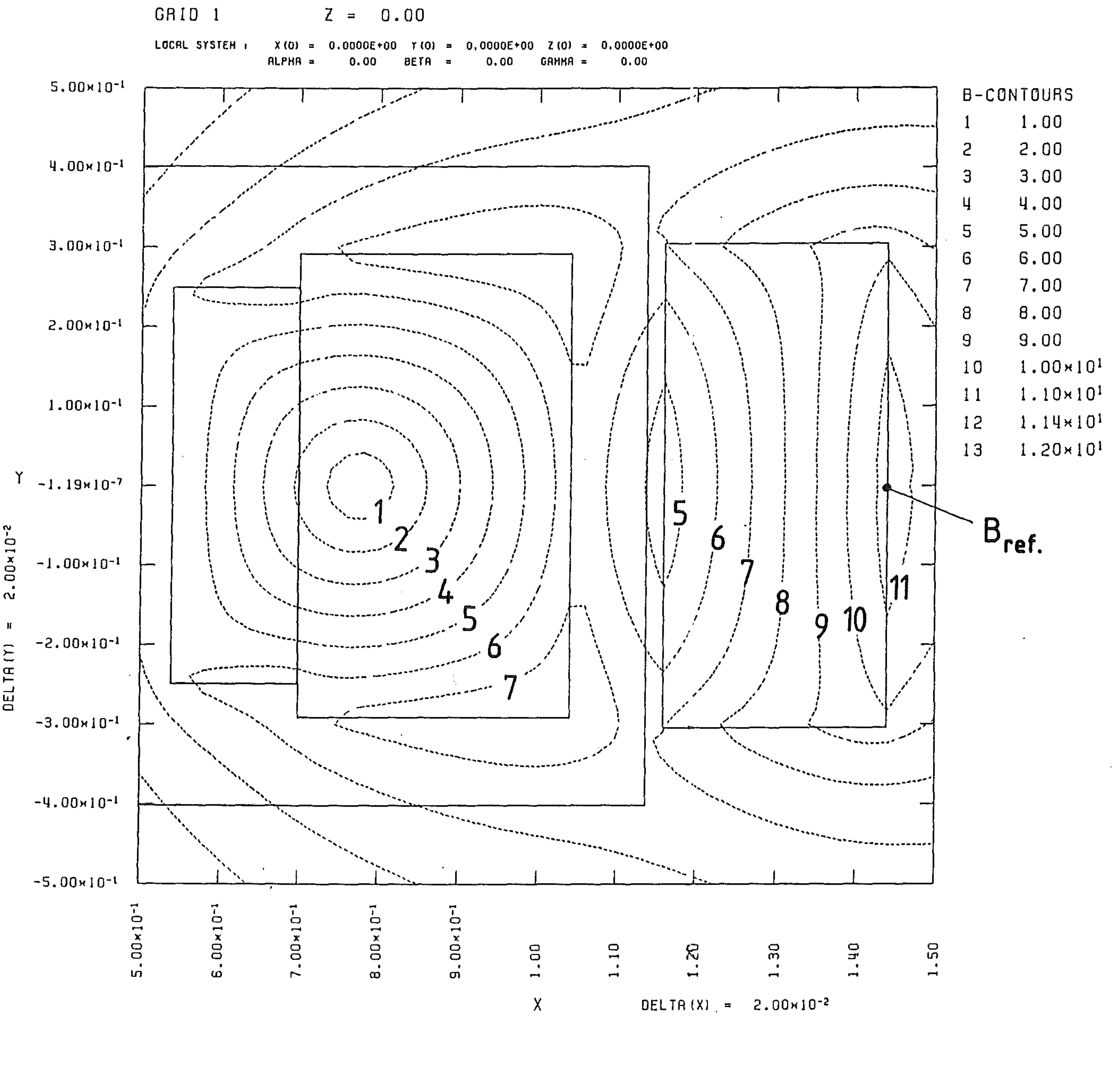

Fig. 4.3-2: B-contours in T of ITC.
(EU-LCT: 18 kA, model coil 22 kA), (x, y in m).

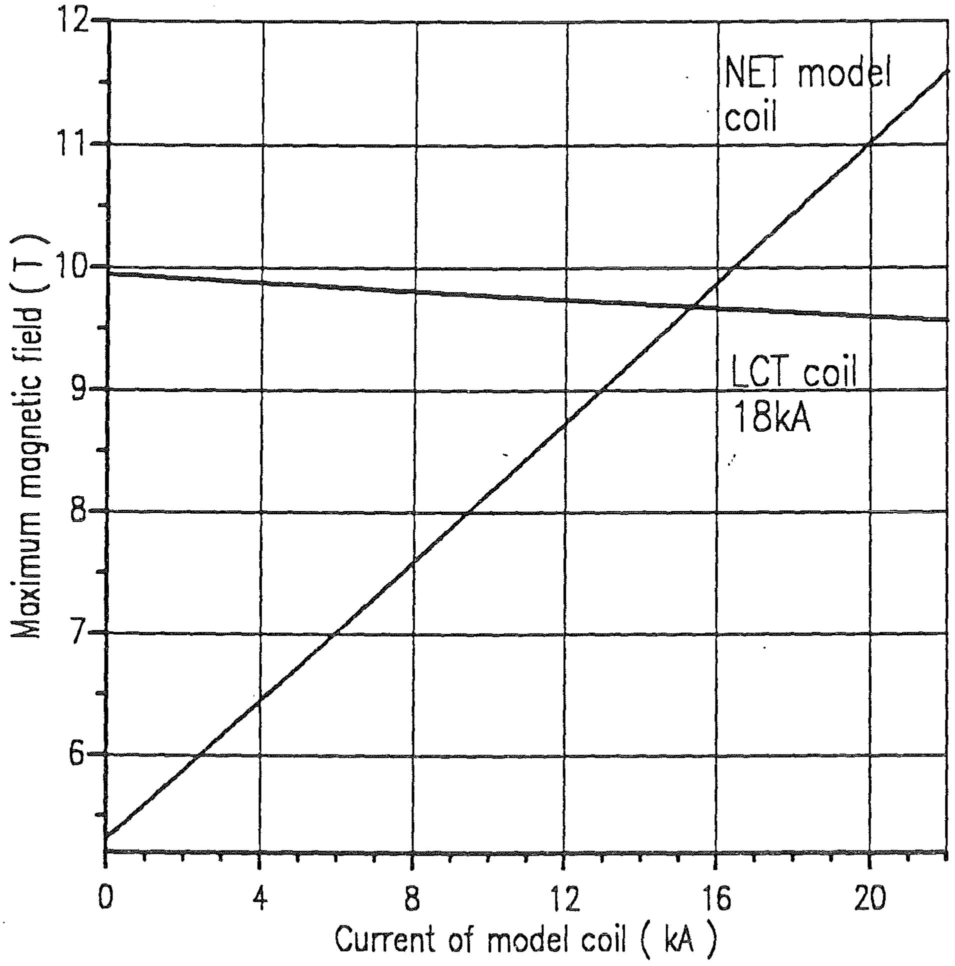

Fig. 4.3-3: Decrease of maximum field at the EURATOM LCT coil during energization of the NET model coil.

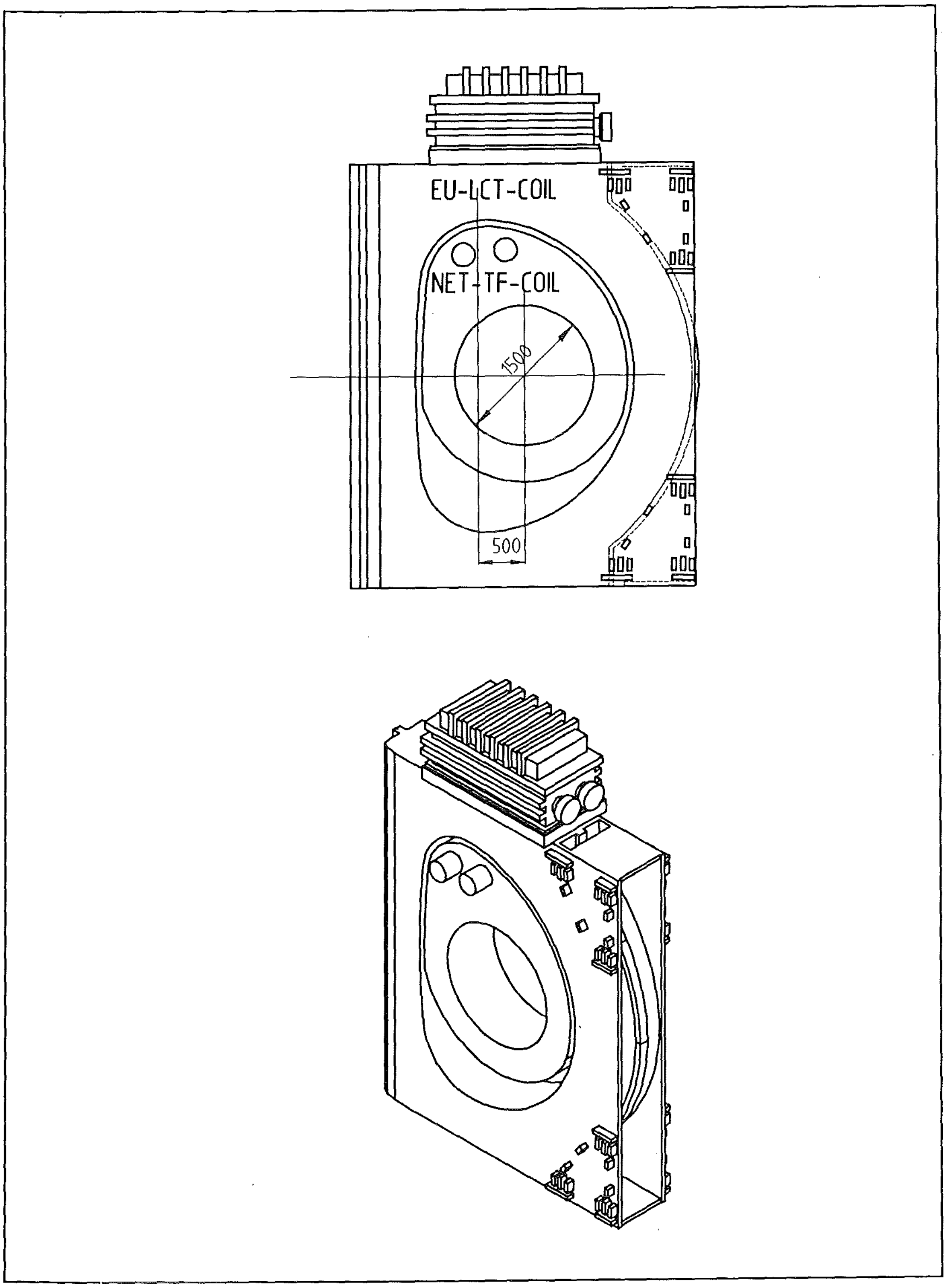

Fig. 4.3-4: TWIN-Test-Configuration.
Inserted model coil upright in the LCT coil.

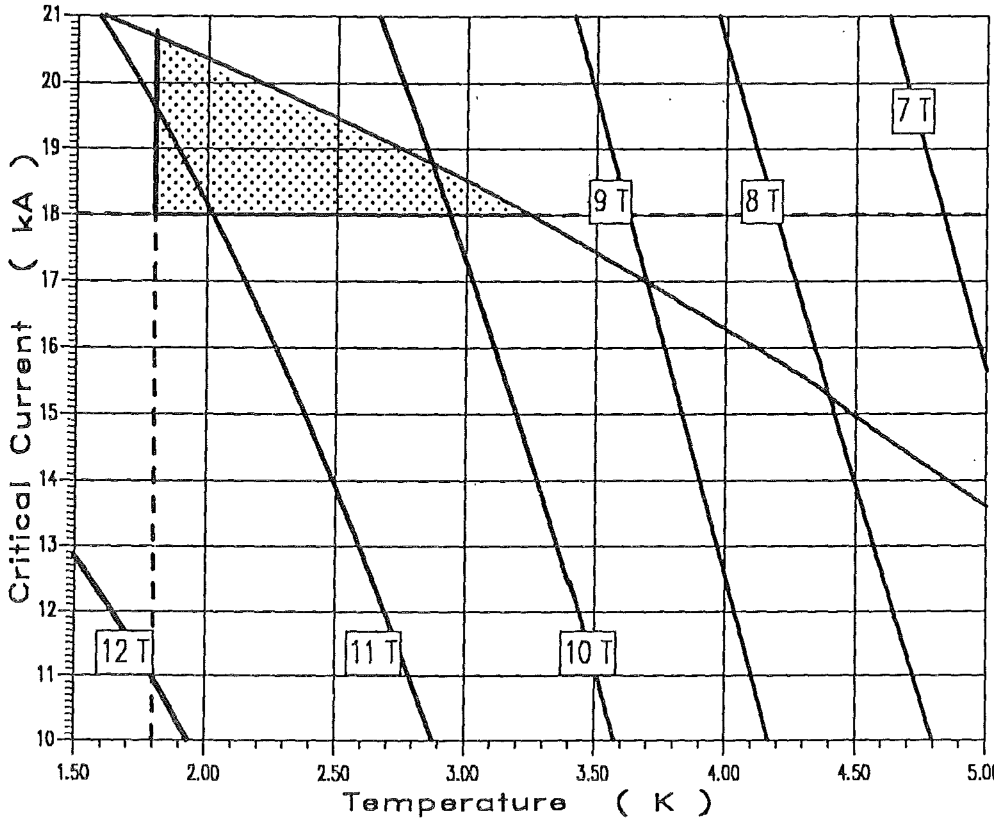

Fig. 4.3-5: Current sharing line for the EU LCT coil in ITC with model coils in upright position.

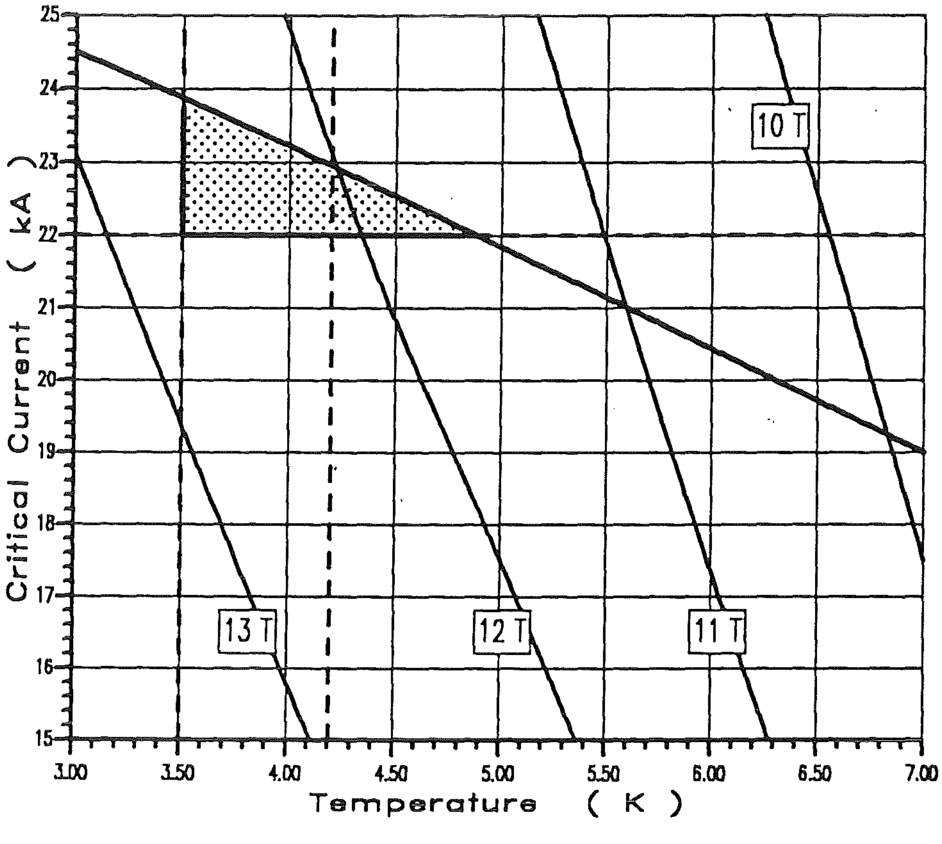

Fig. 4.3-6: Current sharing line for the inserted NET model coils in the ITC.

4.3.2 Investigation of a 60° slope model coil

The difficulties seen for the installation of an inserted upright coil as discussed in the preceding subchapter led to a rotation of the model coil. This measure should produce space for the joints between the pancakes and for supply lines for current and coolant. An angle of 60° was chosen for the rotation. Due to the resultant decrease of the maximum field at the model coil one double pancake was added. In addition to the rotation and the rise of the number of the pancakes the model coil was displaced by 10 cm in axial direction. Fig. 4.3-7 shows the configuration. Table 4.3-4 contains the main characteristics of the 60° slope arrangement and in Table 4.3-5 the properties of the model coil are summarized.

Comparing Table 4.3-5 for the 60° slope model coil arrangement and Table 4.3-2 for the upright model coil no big differences are seen expect for the forces. For the 60° slope arrangement additional forces in z- and y-directions occur due to the rotation of the model coil and the 10 cm displacement from the common coil center.

Fig. 4.3-8 shows the B-contours for the coil arrangement. The results of the inserted upright twin configuration concerning the field behaviour of the LCT coil are also valid in this case.

Different views of the 60° slope arrangement are presented in Fig. 4.3-9 giving some ideas about the installation problems. The driving idea for the 60° slope arrangement was originally to provide more space for feedthroughs and joints beside the LCT coil. This presumed advantage turns out to create big problems for the support structure of the test configuration. A glimpse on Fig. 4.3-9 teaches that the LCT reinforcement structure and the model coil case have to be integrated. This is much more difficult than in the upright solution. A detailed investigation has to clarify whether a solution for the support can be found which is feasible with justifiable expenditure.

Fig. 4.3-10 shows the loadline for the EURATOM LCT coil for this 60° slope arrangement. The safety margin for the temperature is about 1.2 K and 2.2 kA (or about 12 %) for the current. The loadline for the model coil is shown earlier in Fig. 4.3-6.

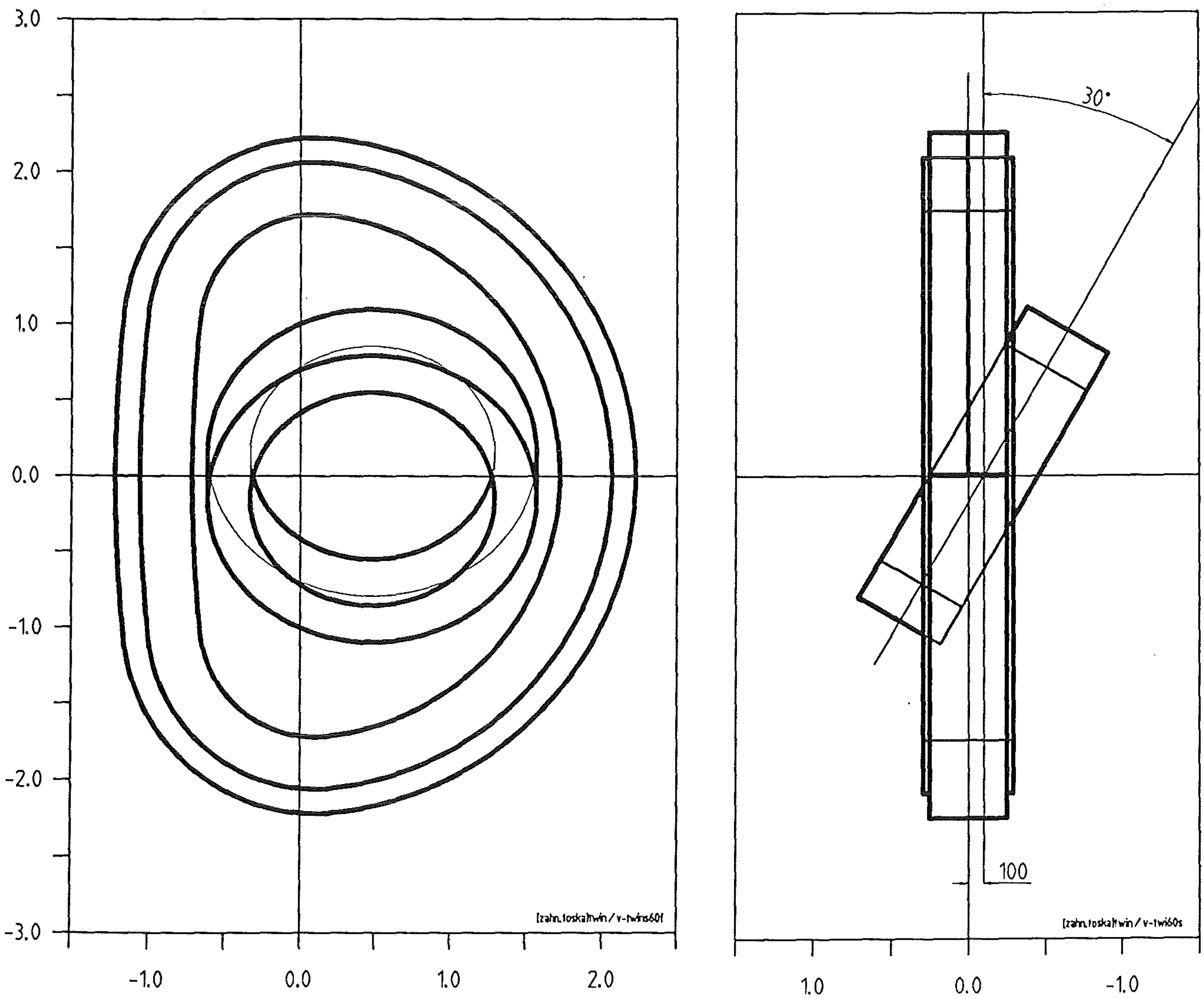

Fig. 4.3-7: View of the rotated model coil. Note the displacement of 10 cm from the common coil center (y = 0).

Table 4.3-4: Main characteristics of the TOSKA ITC with the NET model coil in a 60° slope position

	Unit	NET Model Coil	EURATOM LCT Coil
Operation temperature	K	3.5	1.8
Conductor current Total coil current	kA MA	22 6.335	18 10.584
B_{ref}	T	11.28	7.55
B_{max}	T	11.46	9.76
Force in x-direction (centering force) Force in y-direction (out-of-plane force) Force in z-direction	MN MN MN	1.8 + 8.6 - 2.6	- 1.8 - 8.6 + 2.6
Stored self-energy	MJ	39	253
Total stored energy	MJ	356	
Case thickness	mm	50	50
Hoop stress	MPa		x
Axial pressure	MPa		x
Radial pressure	MPa		x
Shear stress	MPa		x

x has to be investigated together with the reinforcement of the EU coil

Table 4.3-5: Characteristics of the inserted NET model coil with 60° slope.

Winding pack characteristics	Unit	Model coil (60° slope)
X-position of coil center Y-position of coil center	m m	0.0 variable, not yet determined
Current Current density	kA kA/cm^2	22 3.308
Kind of winding		double pancake winding
Number of pancakes Number of layers per pancake Total number of turns		9 x 2 16 288
Inner radius, r_i Radial winding thickness Axial winding width Average winding radius	m m m m	0.81 0.28 0.684 0.95
Average turn length Average conductor length per pancake (= cooling length)	m m	5.97 95.5
Total conductor length (not including spare lengths for fabrication and joints (about 10 %)	m	1719.
Winding cross section Winding volume Estimated winding weight (ρ about 7 t/m^3)	m x m m^3 t	0.19 1.14 8.
Total coil current Ampere-meter	10^6 A 10^6 AM	6.336 37.82
Stored self energy B_{ref} (for 18 kA in LCT coil) B_{max} (for 18 kA in LCT coil) Temperature	MJ T T K	39 11.28 11.46 3.5

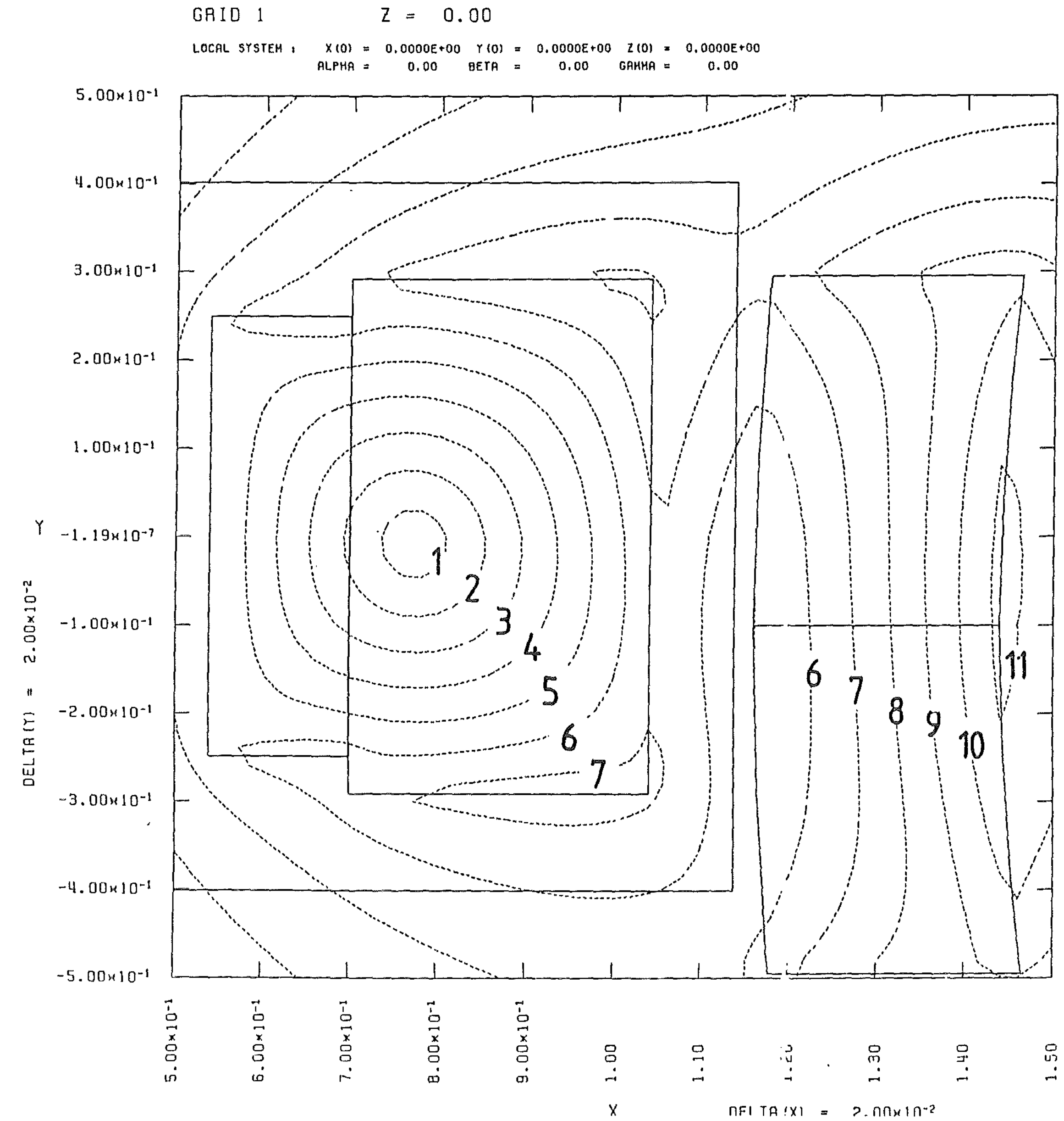

Fig. 4.3-8: B-contours in T of the ITC with a 60° slope model coil.
(EU LCT: 18 kA, model coil: 22 kA) (x, y in m).

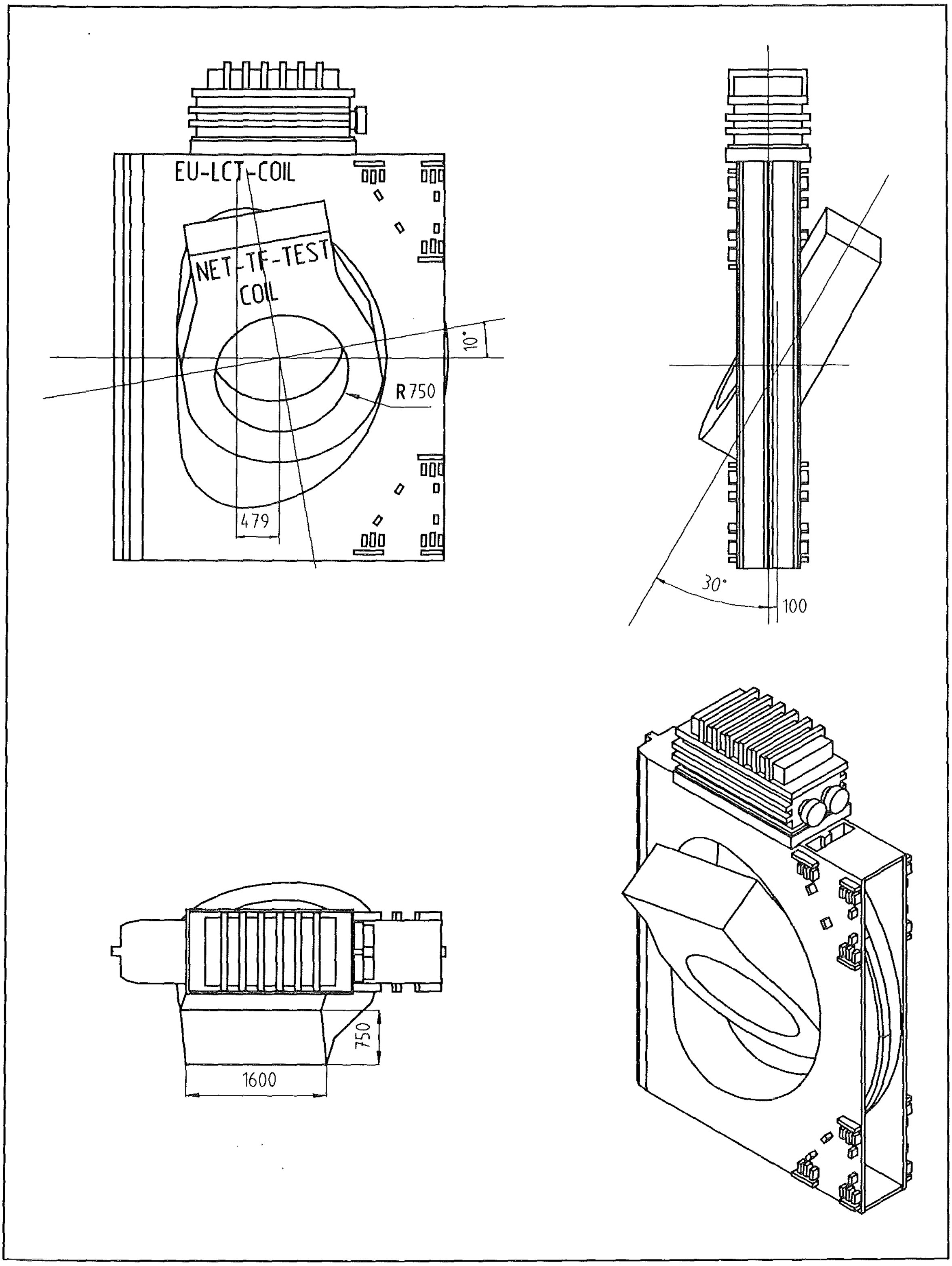

Fig. 4.3-9: TWIN-Test-Configuration. Inserted model coil 60° slope.

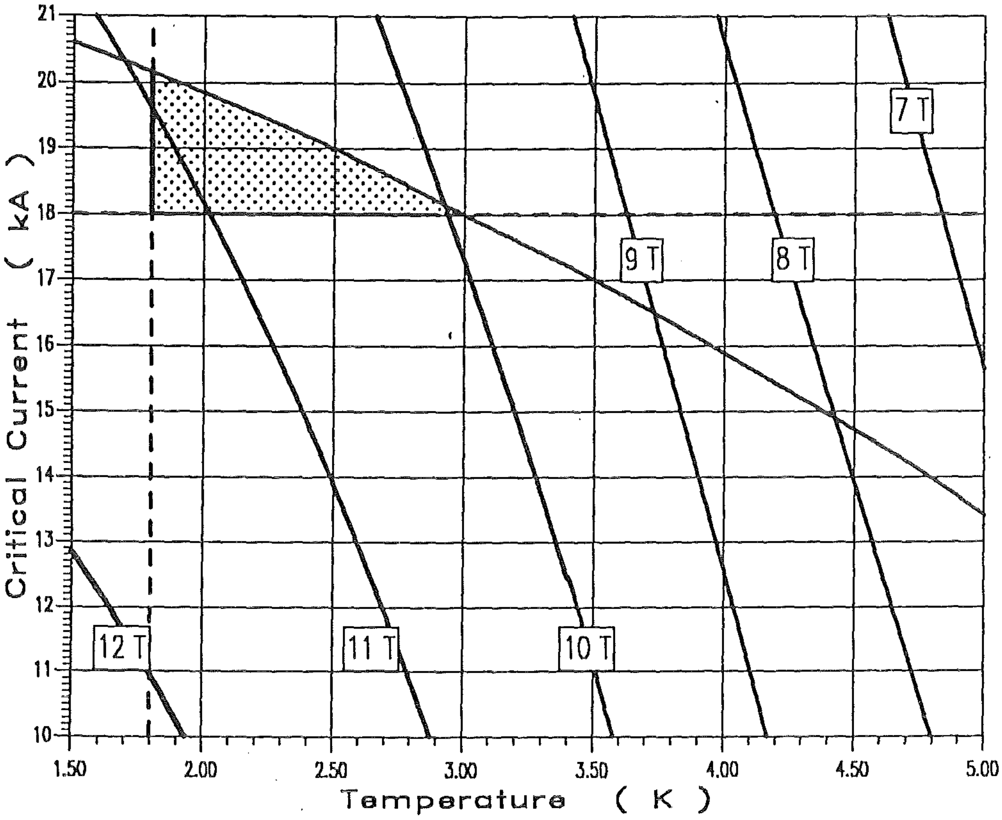

Fig. 4.3-10: Current sharing line for the EU LCT coil in ITC with a 60° degree slope of the model coil.

4.4 The importance of the 1.8 K operation of the LCT coil

So far the 18 kA and 1.8 K operation of the EURATOM LCT coil was considered as a matter of course. In order to emphasize the importance of this extended operation a step back is made i.e. the 13 kA operation of the LCT coil (as in the Cluster C 6) is discussed again and the influence on the model coil will be clarified.

If the Twin configuration ATC is considered as it is now (7 double pancakes, 32 layers per pancake) and only the current in the LCT coil is decreased from 18 kA to 13 kA, then the reference field at the model coil is decreased from 11.69 T to less than 11 T. To compensate this decrease double pancakes (32 layers per pancake) were added and the magnetic field at the reference point was calculated. For 8 double pancakes the field is 11.59 T and for 9 double pancakes 12.18 T. The general behaviour is shown in Fig. 4.4-1 for ATC. The conclusion for ATC is that - without an 1.8 K and 18 kA operation and a 3.5 K and 13 kA operation of the LCT coil - 30 % more conductor is required for the model coil.

The effect is much more dramatic for the ITC as shown in Fig. 4.4-2. The model coil has only about 10 T at an 3.5 K and 13 kA operation of the LCT coil. For compensating this decrease the number of double pancakes has to be doubled from 8 to 16 leading to a conductor length which is almost comparable to that of the ATC. This is due to the fact that the axially added double pancakes contribute only weakly to the field at the reference point in this configuration.

This very preliminary, but impressive consideration challenges the conclusion that the 1.8 K and 18 kA operation of the LCT coil is absolutely necessary for the ITC in order to gain any advantages of the reduced bending radius for the conductor of the model coils. In case of the ATC 2 double pancakes must be added to have a save field margin, i.e. a 30 % conductor length increase (and therefore 30 % cost increase) has to be compared with the costs of the preparation of the LCT coil for the 1.8 K test and also with the fact that the 1.8 K high performance operation of the LCT coil can lead to a confirmation of a NbTi backup solution for NET. The latter fact is hard to quantify in terms of money.

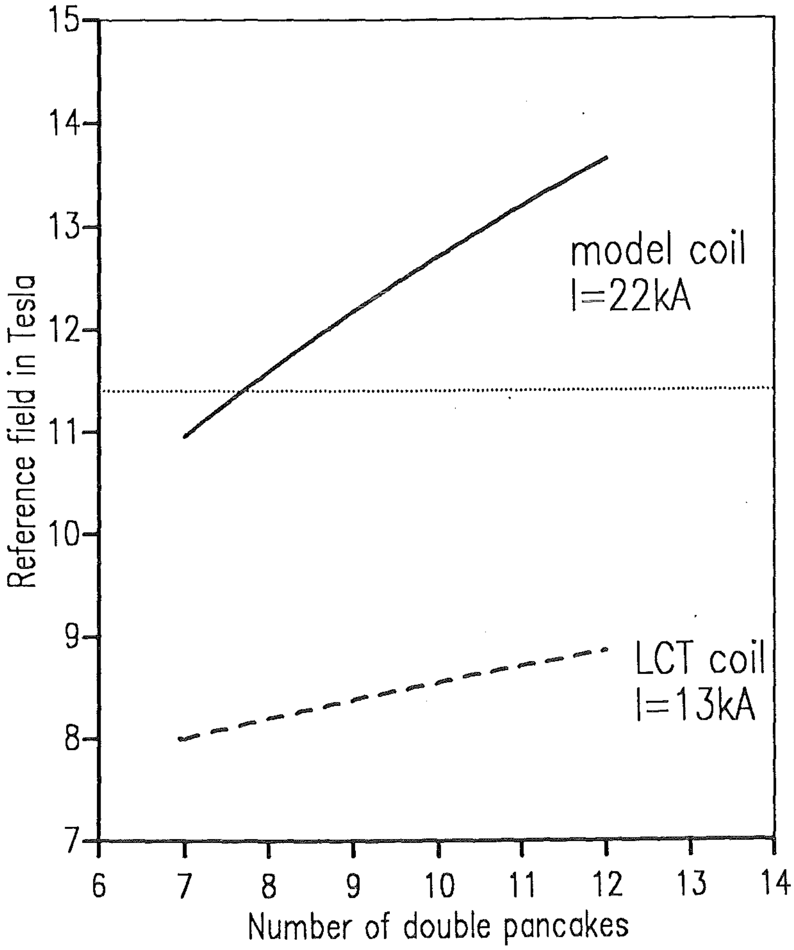

Fig. 4.4-1: Magnetic field at the reference point of the model coils in the ATC in dependence of the number of double pancakes.

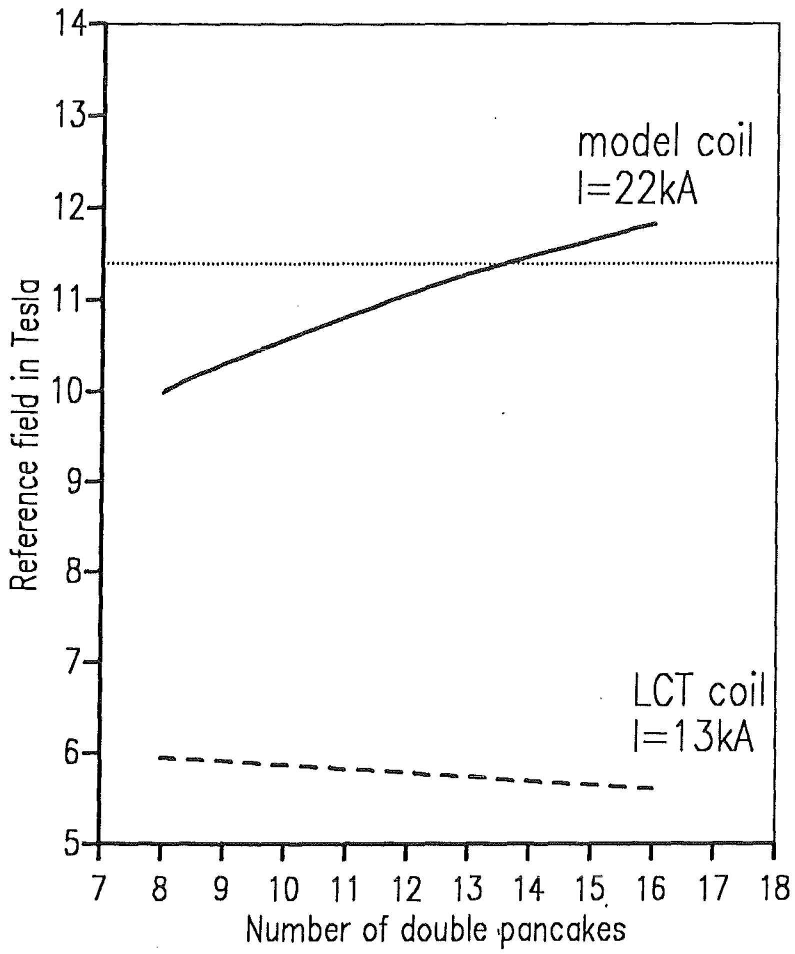

Fig. 4.4-2: Magnetic field at the reference point of the model coils in the ITC in dependence of the number of double pancakes.

[11] R. Flükiger, U. Jeske, P. Komarek, A. Nyilas, P. Turowski, A. Ulbricht, Status of the Development of the KfK NET Toroidal Field Conductor. 15th Symp. on Fus. Techn., Utrecht, The Netherlands, Sept. 19-23, 1988.

5. Forces and stresses

5.1. Stresses in the TF model coils

Calculations were performed with the Finite-Element-Method (FEM) to get the stress distributions, the deformations and the peaks of stresses in the individual TF model coils for the Adjacent Twin Configuration (ATC) (see Fig. 6.1-1) and for the Inserted Twin Configuration (ITC) with an upright model coil (see Fig. 6.2-1) and a 60° slope (see Fig. 6.3-1). The FEM code used for this purpose is ABAQUS 4.7 /12/ together with preprocessor PROLOG /13/ and postprocessor ASKAVIEW 4.0 /14/.

5.1.1 Models for calculation

The technical and physical data of the arrangements are summarized in the Tables 4.2-1 and 4.2-2 for the ATC, in the Tables 4.3-2 and 4.3-3 for the ITC (upright) as well as in the Tables 4.3-4 and 4.3-5 for the ITC (60° slope). The TF model coil system consists of the winding and the casing of 50 mm thickness. The cross-section of the windings is subdivided in 4x4 elements. The casing is modelled with one element layer around the winding and is based on a support which surrounds half the perimeter of the casing (Fig. 5.1-1a) without taking into account the restricted space within the bore of the LCT coil in ITC. One layer of interface elements are used between winding and casing. The geometry and the distribution of the volume loads are symmetric to the z-direction for the ATC and ITC (upright). Therefore only half of the coil system with 24 element layers is modelled. Due to the 60° slope of the ITC the distribution of the volume loads is asymmetric. In this case the whole coil system with 48 element layers has to be modelled. The structures were produced with the preprocessor PROLOG /2/. The distributions of the volume loads are calculated with the program EFFI /15/. Due to the volume forces in x- and z-direction the windings are stretched in radial direction. As a result of the volume forces in the y-direction the following effects are observed in the individual windings:

1. **ATC:** The resulting forces point at the LCT coil (y-direction) and try to parallel the model coil to the LCT coil.
2. **ITC (upright):** The forces of opposite nodes in the y-axis counteract exactly and cause simply a contraction of the winding itself.
3. **ITC (60° slope):** The forces try to place the coil from the sloping position to the upright one.

The stress and displacement analysis is performed with the FEM program ABAQUS 4.7 /12/. The models are constructed with continuum elements of the type C3D8R of the ABAQUS element library. That is a brick element with eight nodes, linear displacement and reduced integration, including hourglass control. The contact problems between the winding and the the casing are solved with interface elements of the type INTER4. These are two dimensional interfaces for use together with three dimensional elements (see Fig. 5.1-1b). There is only one transmission of the normal pressure component. The calculations are performed without friction.

The model coil systems consist of the following numbers of elements and nodes:

- **ATC and ITC (upright):**
  384 C3D8R elements with 625 nodes for the winding
  624 C3D8R elements with 1182 nodes for the casing
  384 INTER4 elements for the interface winding/casing.
- **ITC (60° slope):**
  768 C3D8R elements with 1200 nodes for the winding
  1284 C3D8R elements with 2270 nodes for the casing
  768 INTER4 elements for the interface winding/casing.

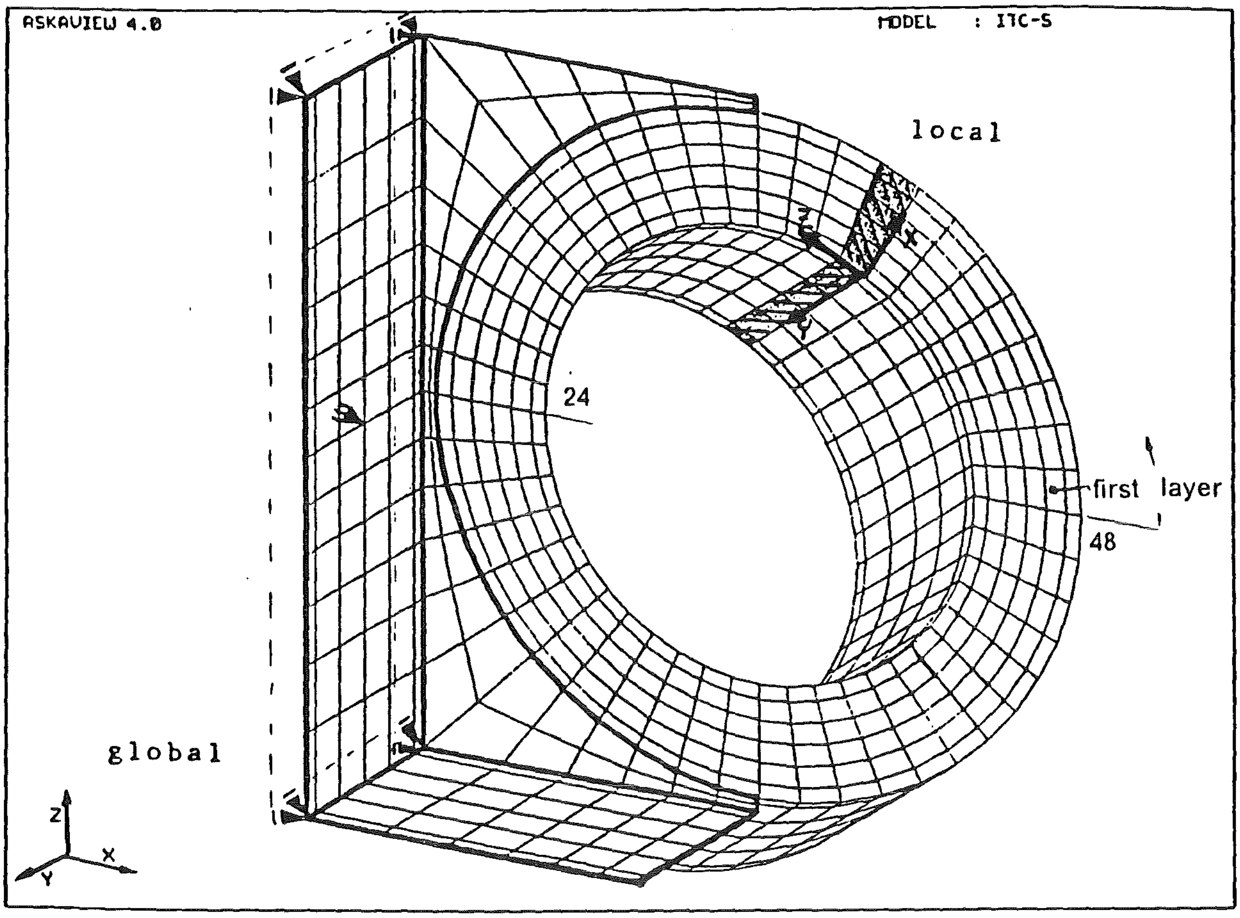

Figure 5.1-1a: FEM model of the ATC and ITC
Presentation of the local and global coordinate system, the boundary conditions and the counterclockwise arrangement of the layers

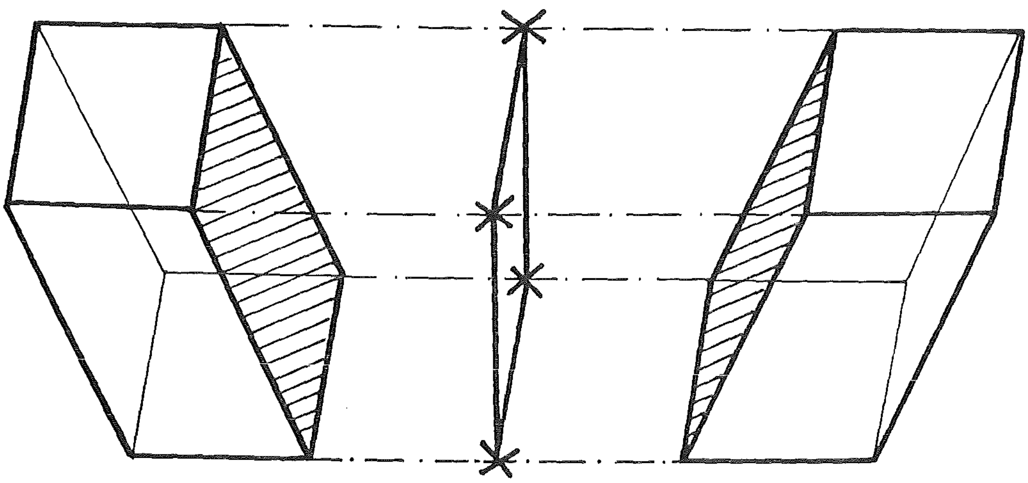

Figure 5.1-1b: Used element types for contact problems
One interface element (INTER4) between two brick elements (C3D8R)

Since the physical support of the model coil systems against the LCT coil system is not yet determined the following boundary conditions are selected:

- For all three model coil systems all nodes of the front of the casing are constrained in x-direction and the node in the centre of the front, especially marked on Fig. 5.1-1a, is pinned in the coordinate system.
- All nodes of the central axis in z-direction of the front of the ITC (60° slope)-casing are fixed in the local y-direction.
- For the ATC and ITC (upright) all nodes of the plane of symmetry (xy,z=0) are suppressed in z-direction.
- The nodes of the lateral face of the ATC casing are also suppressed in y-direction. This boundary condition simulates the connection to the LCT coil.

The material properties of the windings were assumed to be orthotropic in the local coordinate system with the following values:

Winding	Modulus of elasticity	Poisson's ratio
E_1 (radial)	80.0 GPa	0.3
E_2 (axial)	80.0 GPa	0.3
E_3 (longitudinal)	120.0 GPa	0.3
G	20.0 GPa	

Isotropic behaviour is assumed for the casing with the following values:

Casing	Modulus of elasticity	Poisson's ratio
	205.0 GPa	0.3

5.1.2 Numerical analysis and results

A local coordinate system is introduced for all elements of the winding. The local x-axis for the elements is in radial direction, the local y-axis is in axial direction and the local z-axis is perpendicular to the xy-plane (Fig. 5.1-1a). In the lists of the results

- all displacements (mm) are given in the **global coordinate system**,
- all stresses (MPa) are given in the **local coordinate system**.

In the following Table 5.1.2-1 the ranges of the radial $\sigma(x)$, axial $\sigma(y)$, tangential $\sigma(z)$ and shear stresses - $\tau(xy)$, $\tau(yz)$ and $\tau(zx)$ - are summarized:

	ATC		ITC upright		ITC 60° slope	
	MPa		MPa		MPa	
	from	to	from	to	from	to
$\sigma(x)$	-51.7	-6.3	-44.0	-2.3	-61.1	2.1
$\sigma(y)$	-48.2	-7.0	-51.8	-6.5	-139.0	-1.4
$\sigma(z)$	45.7	163.0	78.1	152.0	-17.0	231.0
$\tau(xy)$	-10.9	8.3	-15.5	15.5	-37.1	31.1
$\tau(yz)$	-1.3	1.1	-2.1	2.1	-32.5	29.3
$\tau(zx)$	-9.6	7.2	-2.8	2.6	-13.9	20.5

Table 5.1.2-1: The peak-stresses in the windings

The distribution of the radial stresses $\sigma(x)$ in the windings shows a typical course in the x-direction. The values increase from the inside face to the outside one. For the ATC and ITC (60° slope) maxima are formed in the area of the support on the lateral face where the winding presses against the casing. The maximum tangential stresses $\sigma(z)$ are found at the inside face and decrease to the outside. The axial stresses $\sigma(y)$ have the following distribution in the axial direction:

1. **ATC:**

   The values increase from the negative y-direction to the positive one. The resulting y-forces point at the positive y-direction.

2. **ITC (upright):**

   The values increase from the lateral face to the central one. The y-forces of opposite nodes with respect to the y-axis counteract each other. Therefore only a contraction of the winding occurs.

3. **ITC (60° slope)**

   The distribution of the stresses is similar in the upper and in the lower part of the winding. The values increase in the direction of the resulting y-forces. Two maxima are formed in the area of the support, that is on the lateral face where the winding presses against the casing.

The important shear stresses $\tau(zx)$ show the characteristic islands of stresses with positive and negative values distributed over the circumference.

The maximum stresses of the three windings, the target test values and the maximum displacements are shown in the Tables 5.1.2-2 and 5.1.2-3:

	Target Test Value MPa	ATC MPa	ITC upright MPa	ITC 60° slope MPa
Radial stress $\sigma(x)$	-40.0	-51.7	-44.0	-61.1
Axial stress $\sigma(y)$ (Toroidal stress)	-140.0	-48.2	-51.8	-139.0
Tangential stress $\sigma(z)$ (Hoop stress)	140.0	163.0	152.0	231.0
Shear stress	30.0			
Shear stress $\tau(xy)$		-10.9	-15.5	-37.1
Shear stress $\tau(yz)$		-1.3	-2.1	-32.5
Shear stress $\tau(zx)$		-9.6	-2.8	20.5

Table 5.1.2-2: Target test values and maximum stresses in the windings

	x mm	y mm	z mm
ATC	1.00	0.37	1.90
ITC (upright)	2.25	0.24	0.76
ITC (60° slope)	2.93	7.10	-5.25

Table 5.1.2-3: Maximum displacements in the windings

The deformations for the ATC are shown in the Figs. 5.1-2 and 5.1-3, for the ITC (upright) in the Figs. 5.1-4 and 5.1-5 as well as for the ITC (60° slope) in the Figs. 5.1-6 and 5.1-7. The figures were produced with the postprocessor ASKAVIEW 4.0 /15/.

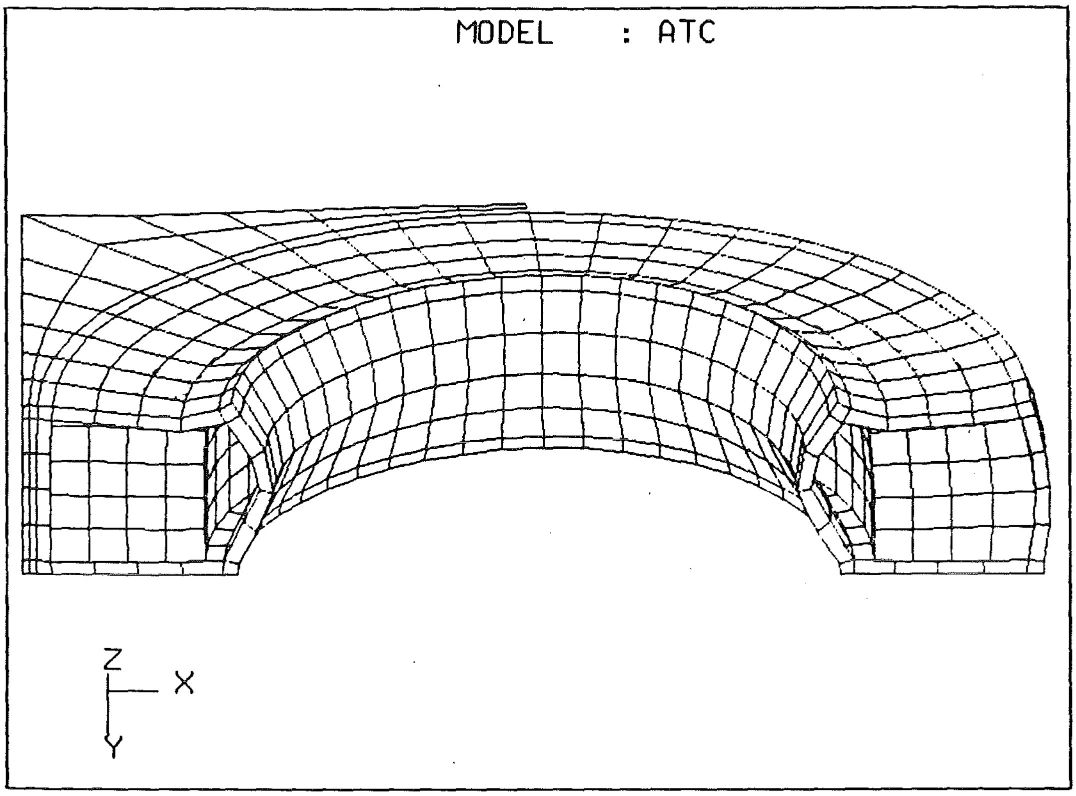

Figure 5.1-2: Interior view in the deformed structure of the ATC
Scale factor: 200

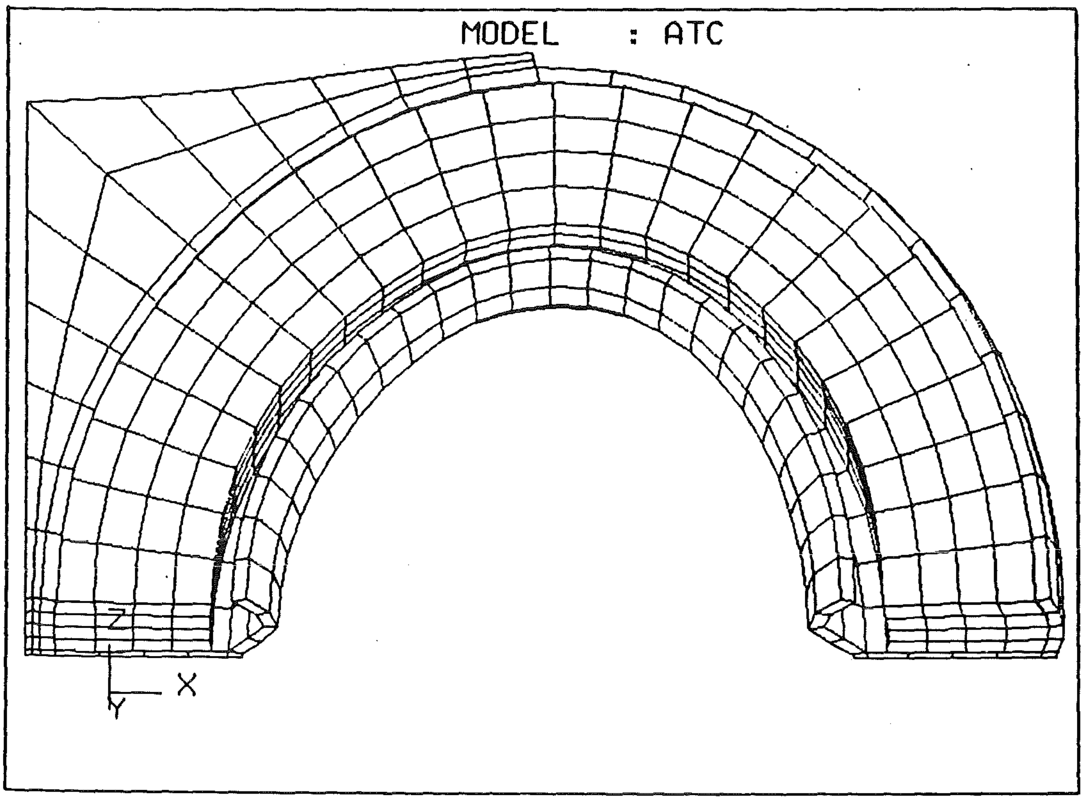

Figure 5.1-3: Interior view in the deformed and opened structure of the ATC
Scale factor: 200

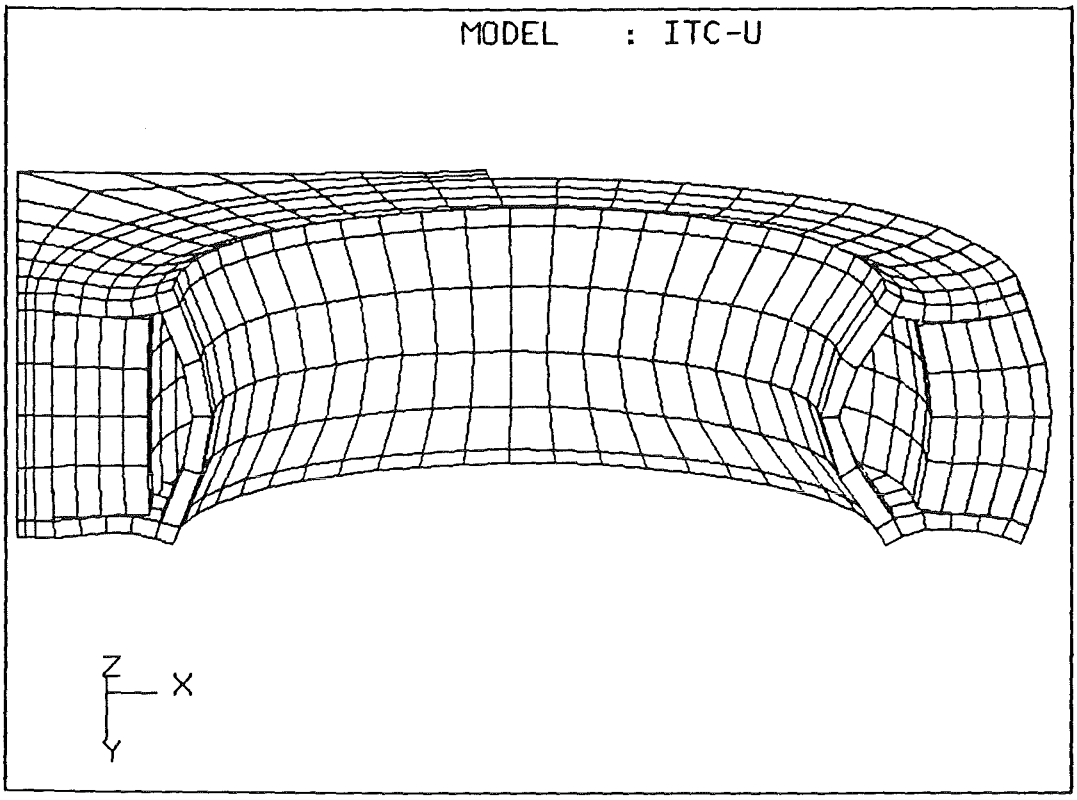

Figure 5.1-4: Interior view in the deformed structure of the ITC (upright)
Scale factor: 200

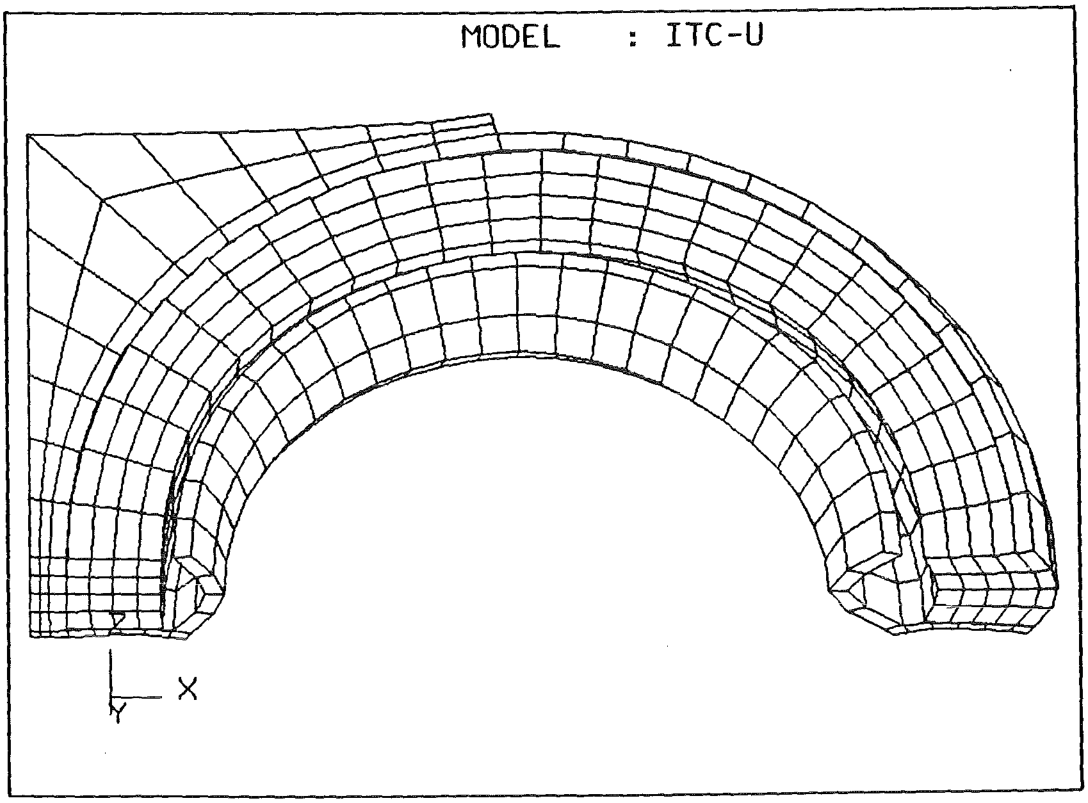

Figure 5.1-5: Interior view in the deformed and opened structure of the ITC (upright)
Scale factor: 200

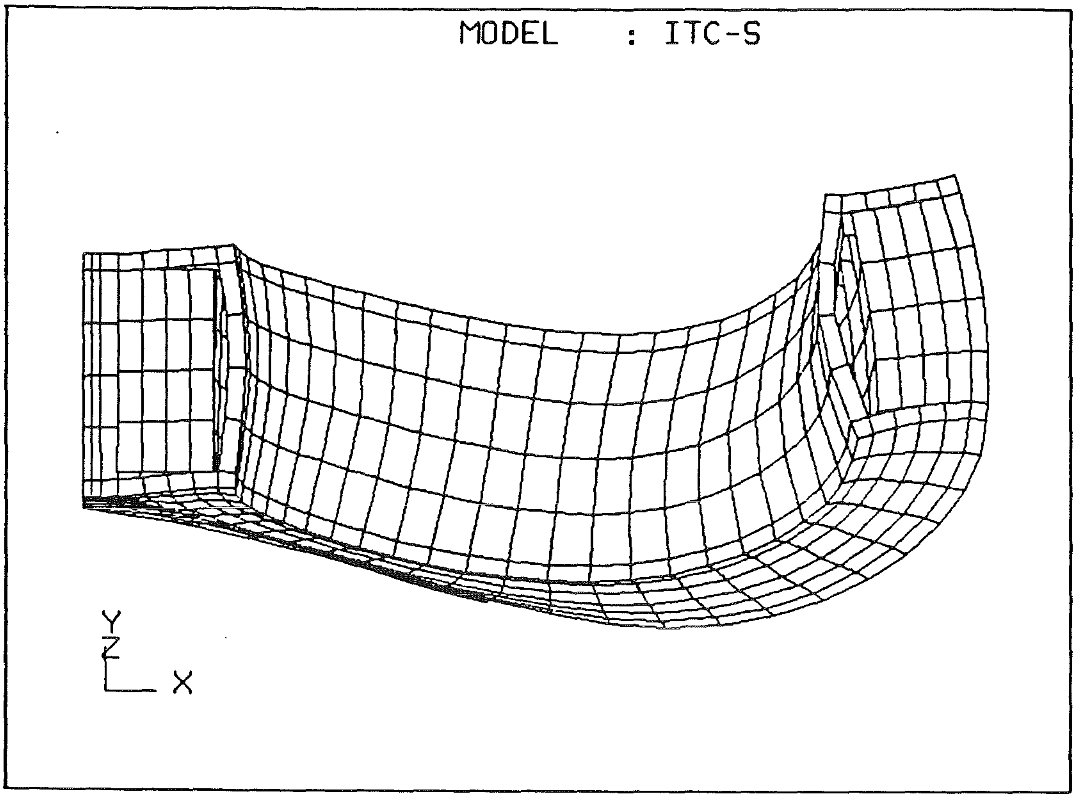

Figure 5.1-6: Interior view in the deformed structure of the ITC (60° slope)
Scale factor: 100

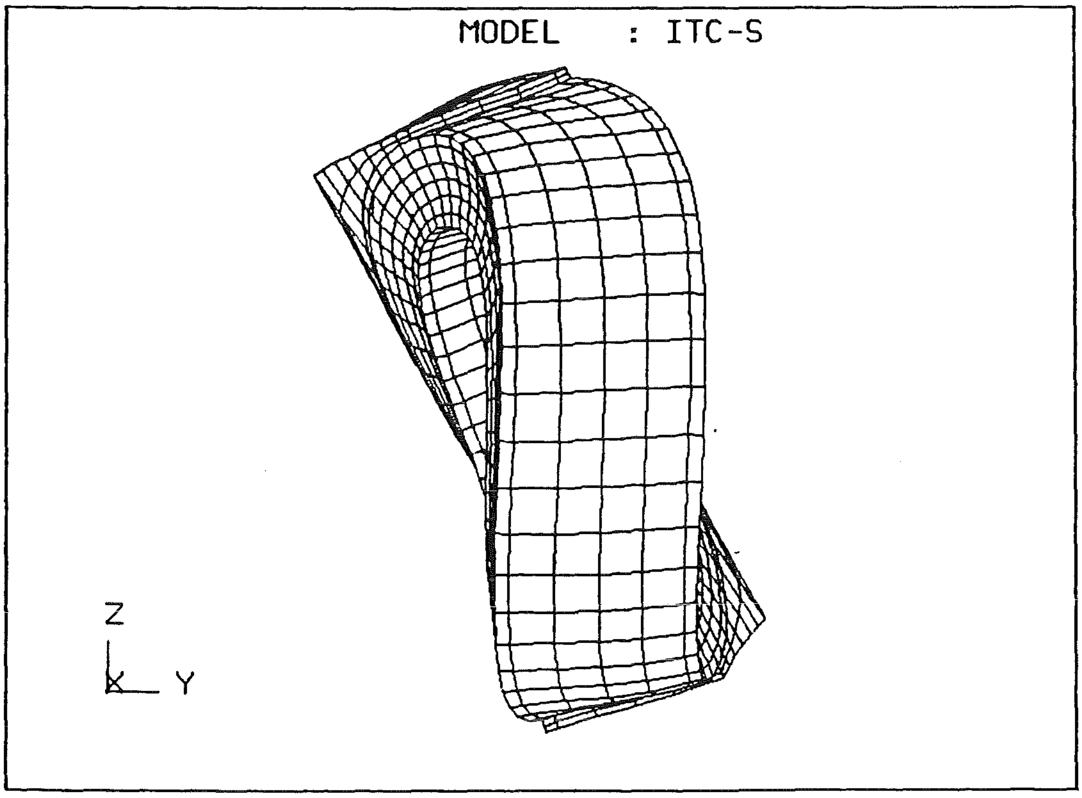

Figure 5.1-7: Deformed structure of the ITC (60° slope)
Scale factor: 100

Finally the maximum principal stresses are given in Table 5.1.2-4:

	maximum principal stresses MPa	location between layers
ATC	163	1 - 48
ITC (upright)	152	11 - 12
ITC (60° slope)	231	7 - 8

Table 5.1.2-4: Maximum principal stresses in the windings

The principal stresses represent the relevant stresses in the structure independent of the specified coordinate systems. The location of the peaks are indicated in Table 5.1.2-4 with respect to the layers. The maxima occur at the inner radius always.

The Von Mises reference stresses attain the maximum values of 487 MPa in the casing of the ITC (60° slope). The allowed reference stress amounts to 700 MPa.

5.1.3 Conclusion and remarks

The relative high peak values of the ITC (60° slope) are due to the out-of-plane bending which can be seen in Fig. 5.1-7, therefore additional bending stresses are superimposed.

In comparison with the values of the NET TF coil, the ATC as well as ITC (upright) the maximum tangential stresses agree quite well. The radial stress of the ITC (upright), the axial stress and the shear stresses - $\tau(xy)$ and $\tau(yz)$ - of the ITC (60° slope) show also a good agreement but all other stress values differ from 29 up to 96% to the target test values. Summarizing the ITC (60° slope) arrangement fulfills best the target test values.

The analysis gives a general impression of the stress distribution and deformation of the coil systems. For a further analysis following items must be considered in more detail:

- Better knowledge of the different moduli of elasticity and thermal expansion coefficients of the winding
- Prestressing of the systems by cooling down as first load step
- Possible variation of elements for the FE-models
- Realistic mechanical coupling between model coil and LCT coil.

All these should lead to a better understanding of the support structure for the model coil test stand.

Literature:

/12/ Hibbitt, Karlsson & Sorensen,Inc.
ABAQUS USER MANUAL, Version 4.7
35 South Angell Street, Providence, R I 02906

/13/ PROLOG, Pre- and Postprocessor
GfS, Gesellschaft für Strukturanalyse mbH
Wermutsbrunnstr. 15, 5100 Aachen

/14/ ASKAVIEW, Version 4.0 User Manual
Femview Limited/GB
IKOSS Stuttgart/BRD

/15/ S.J. Sackett
UCID 17621 "EFFI-a code for calculating the electromagnetic field, force and inductance in coil systems of arbitrary geometry", 1977

6. Installation of the test rig

The three Twin configurations with adjacent (ATC) and inserted coil (ITC), one with an upright model coil and another with 60 degrees slope are already discussed in chapter 4. All three options have the following advantages compared to the cluster configuration investigated in the earlier report [1]

- It is possible to install each of the three test arrangements into the existing vacuum vessel of the TOSKA facility.
- No enlargement of the LN_2 shield is necessary.
- Modifications of the vacuum vessel itself are moderate; only additional ports for the current leads have to be installed.
- The weight of the vessel including the EU-LCT coil, model coil, and additional structure can be supported by the concrete bottom of the pit without any reinforcement of the existing bottom; therefore it is not necessary to remove the transfer lines and the vessel from the pit for modifications.

All three Twin arrangements require reinforcement of the EU-LCT coil in order to sustain the forces and stresses at an operating current between 16 and 20 kA which is above the design value of 11.4 kA. That is the price to be paid for the higher performance of the EU-LCT coil.

For the 1.8 K cooling of the EU-LCT winding an additional cryostat and helium transfer lines are required.

The mechanical pressure in axial direction is still below the NET value and consequently an artifical load has to be applied as proposed in the first report [1].

6.1 Installation of the ATC

This configuration (as discussed in chapter 4) has to be slightly modified in order to achieve enough space for the reinforcement structure of the EU-LCT coil. In chapter 4, Fig. 4.2-2, the model coil was shown in the center of the vessel and the LCT coil rotated by an angle of 9 degrees with respect to the model coil. In this position the available space for the reinforcement is limited and the installation of the structure would be difficult. A reinforcement of the LCT coil outside the vessel is not possible because the maximum load of the crane is 500 kN and coil together with reinforcement structure exceed this value. Therefore the position of both coils where rearranged as shown in Fig. 6.1-1, but the relative position to each other was kept. The calculations of magnetic field, forces and stresses as reported in chapter 4 and 5 are therefore still valid.

The position of the LCT coil in the center of the vessel has the advantage that the same kind of supports and tension rods can be used as for the domestic test of the LCT coil [16].

In a first step a single coil test of the LCT coil at subcooled forced flow conditions (1.8 K) without NET model coil will be performed. This provides an excellent pretesting of the facility already at a time where the model coils are not yet available. Also this test can be answer whether the LCT coil conductor design represents a backup solution for the NET TF conductor or not.

In a second step the NET model coil can be installed without difficulties or space restrictions and tested in the background field of the LCT coil.

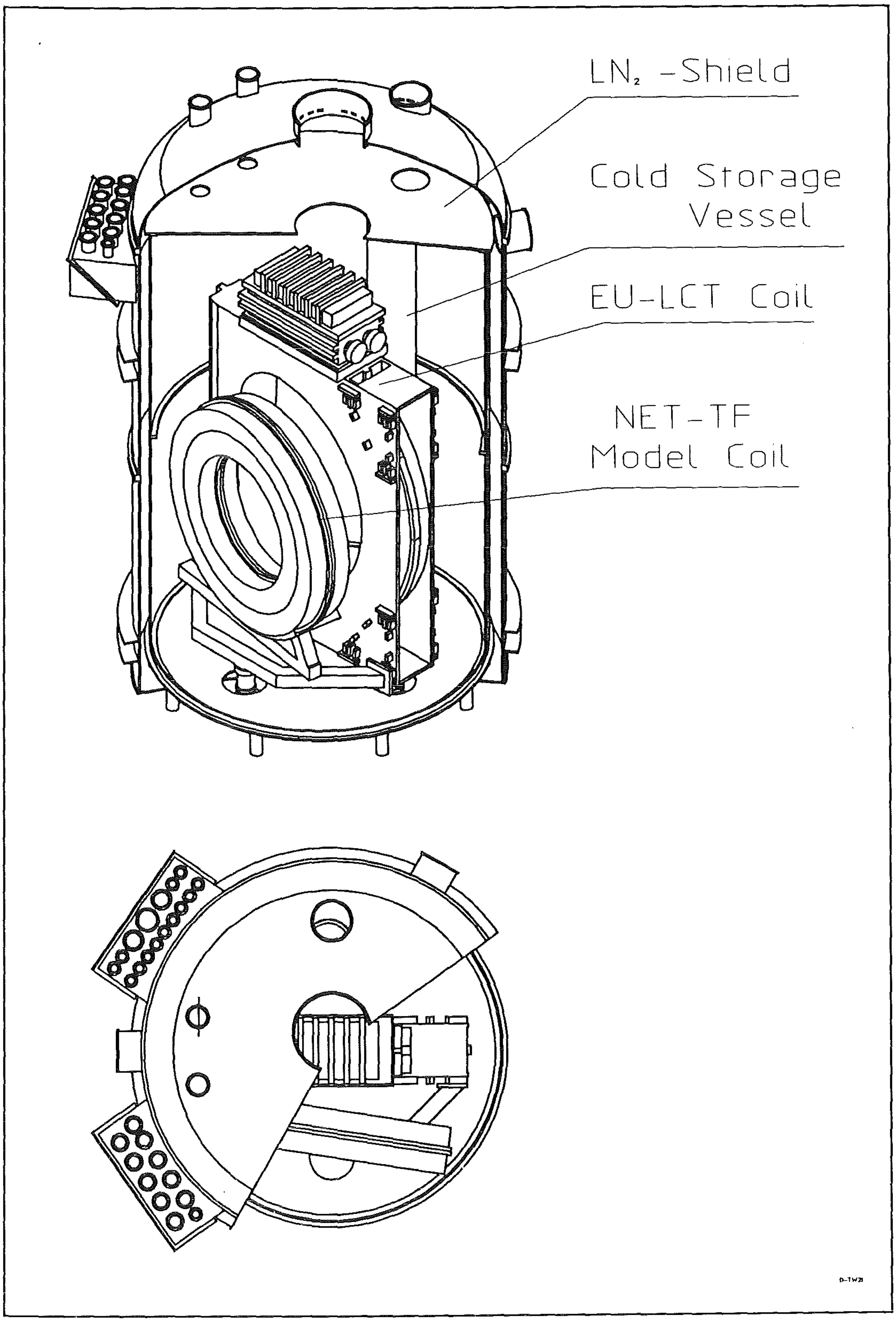

Fig. 6.1-1 Coil arrangement in the vacuum vessel with adjacent NET model coils.

6.2 Installation of the ITC with inserted NET model coils in upright position

An installation inside the LCT coil as shown in Fig. 6.2-1 is possible. This installation can be done after the 1.8 K test of the LCT coil. The reinforcement of the LCT coil has to be constructed in any case in individual parts which will be mounted inside the vacuum vessel and can partly removed for the installation of the NET model coils.

One problem of this configuration is the limited space inside the bore of the LCT coil for the joints of the individual pancakes and the feedthroughs of the current leads. A preliminary design of this region is shown in Fig. 6.2-2. However, the final decision whether an upright installation inside the LCT coil is possible or not can only be made after a more detailed design of the NET model coil header region with the final NET TF conductor.

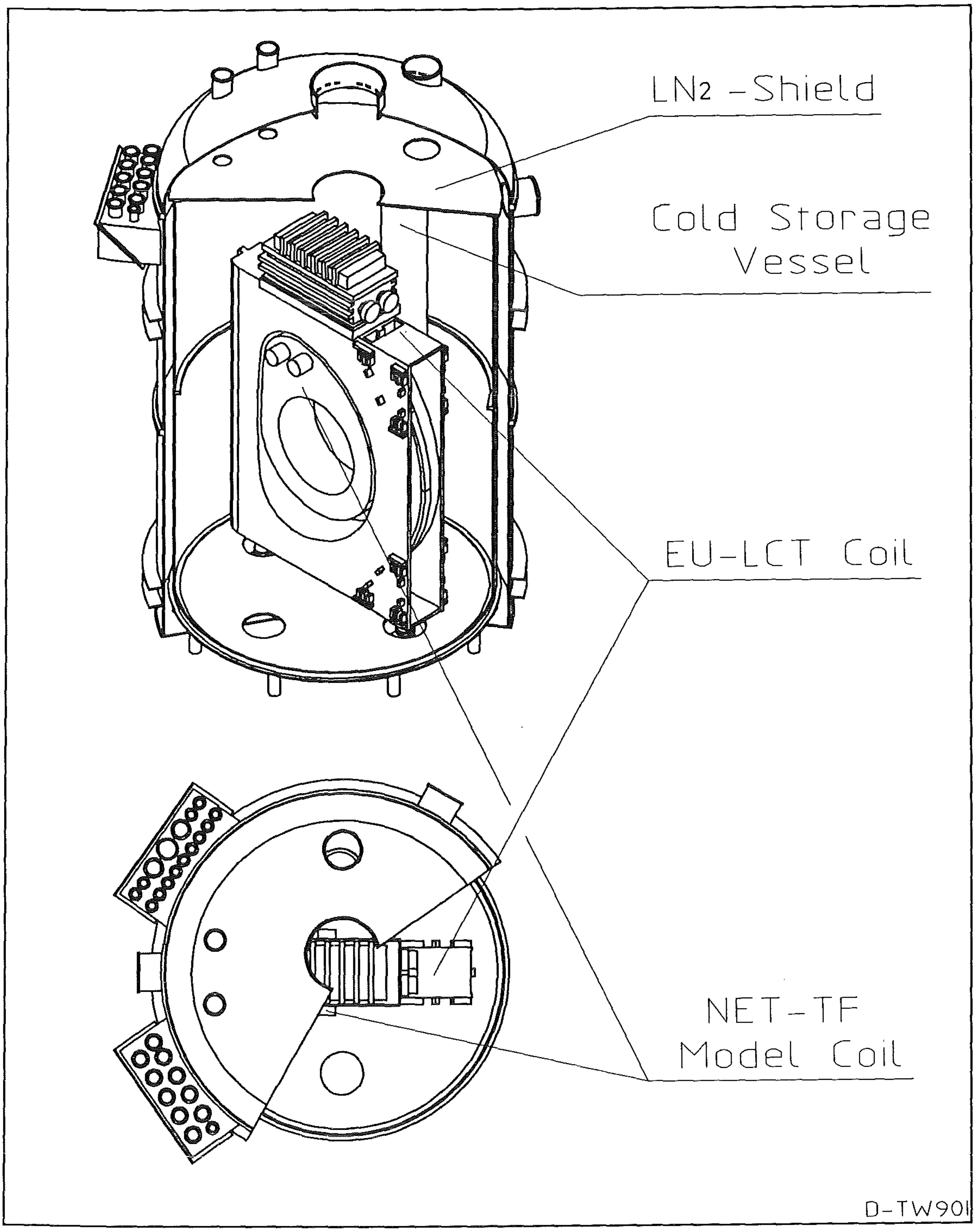

Fig. 6.2-1 TWIN-Test-Configuration with inserted model coil upright in the LCT-coil.

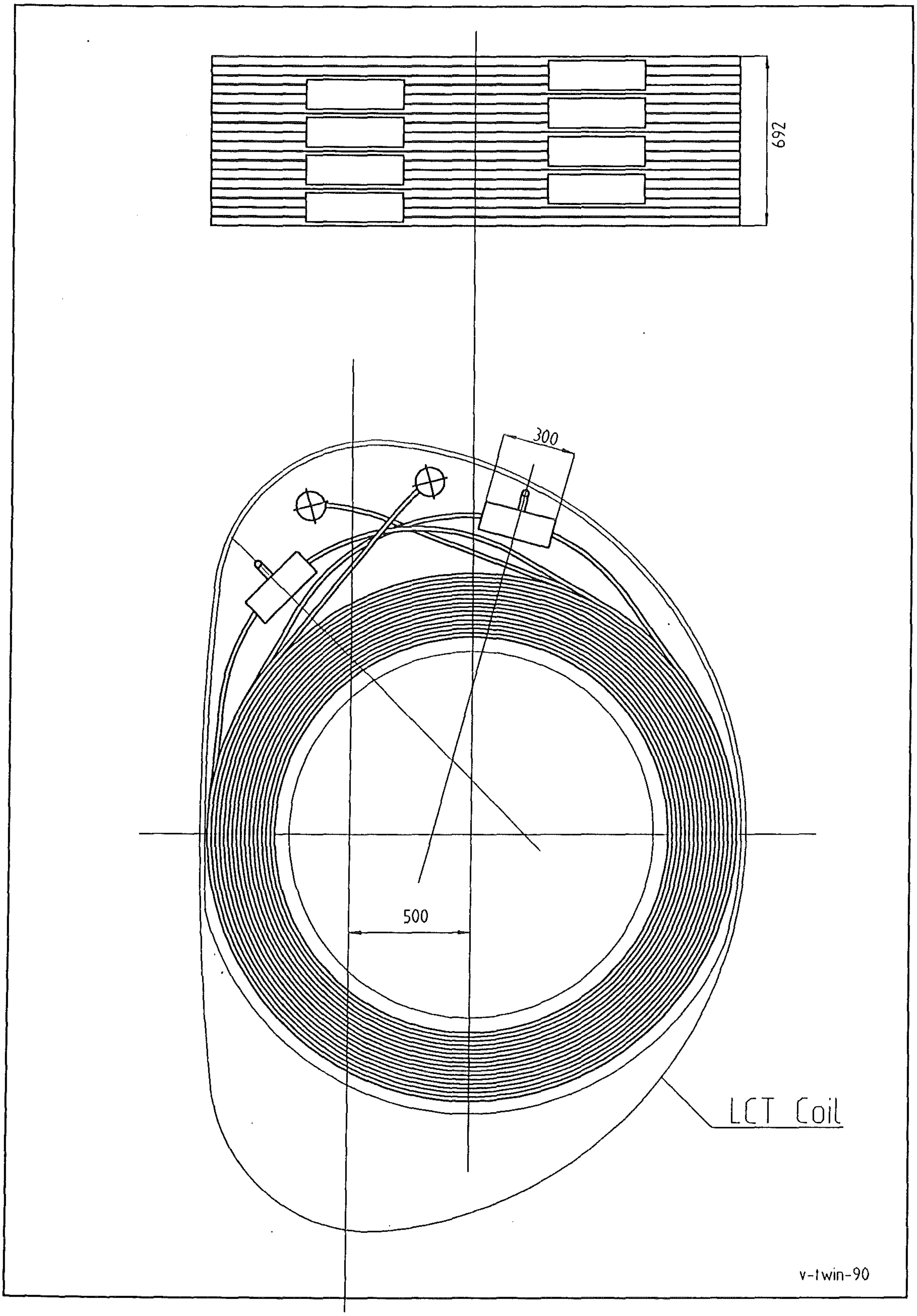

Fig. 6.2-2 Header region of ITC with inserted model coil in upright position in the bore of the LCT coil. (Dimensions in mm).

6.3 Installation of the ITC with inserted NET model coils with a 60 degree slope

The NET model coil was rotated as shown in Fig. 6.3-1 in order to achieve more space in the header region for the connection of the pancakes and installation of the feedthroughs for the current leads. A possible solution of the header region was preliminary designed and can be seen in Fig. 6.3-2.

At a first glance it seems that the space problem can be solved by this solution but the problem is now shifted to the reinforcement design of the LCT coil.

A detailed design of the NET coil header region including the final NET TF conductor is required in order to decide which insert configuration is the better one from an engineering point of view.

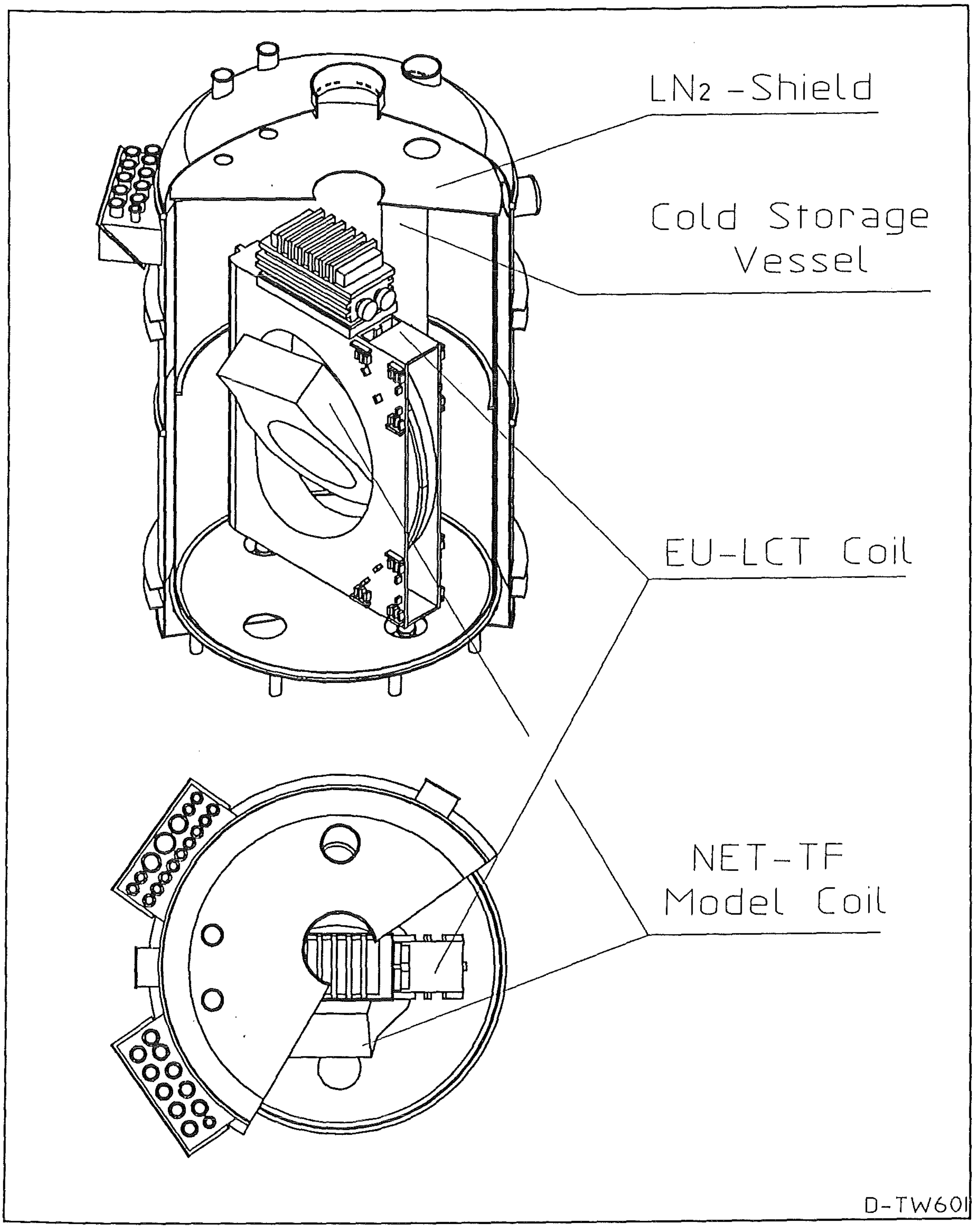

Fig. 6.3-1 ITC with a 60° slope model coil.

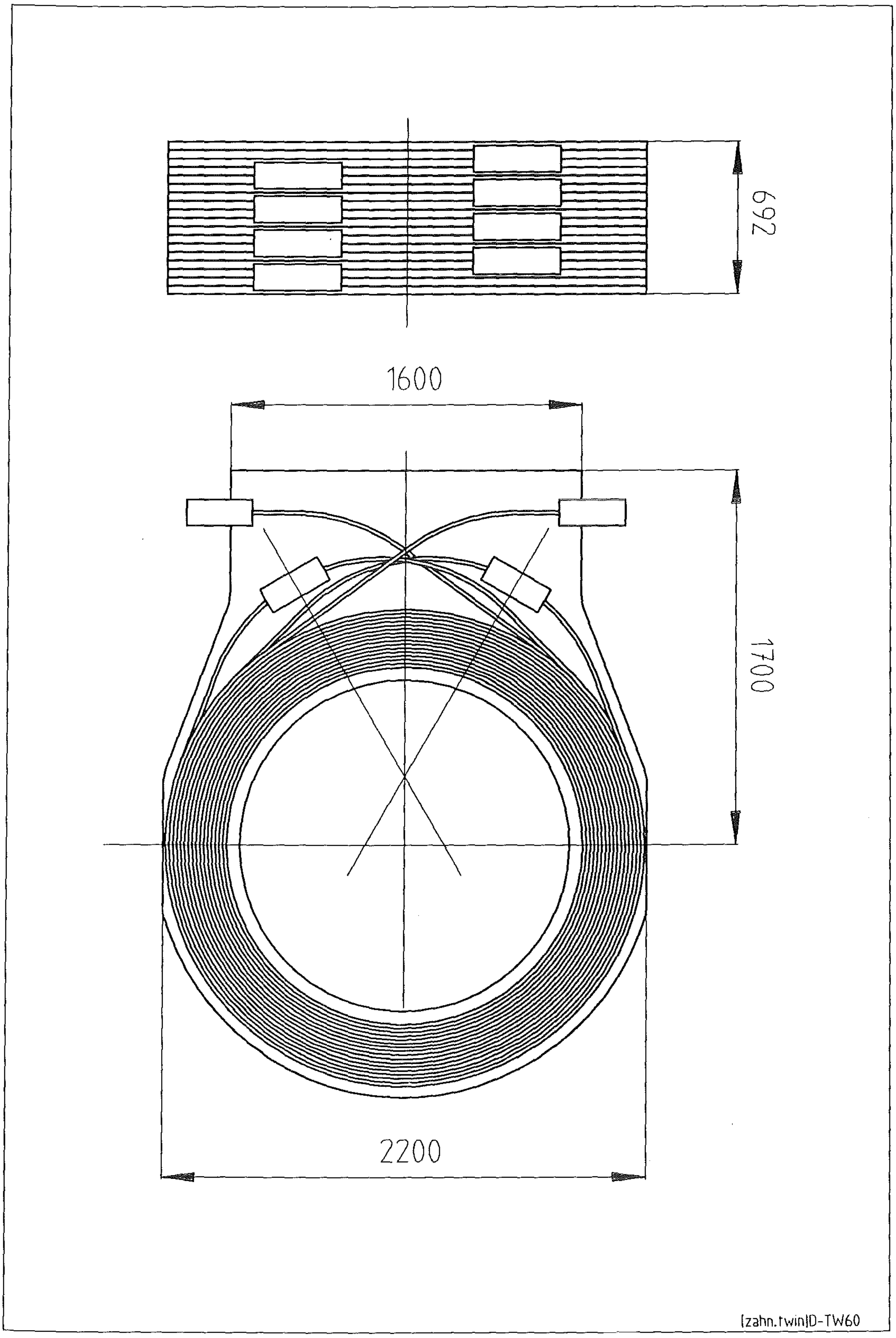

Fig. 6.3-2 Header region of the inserted model coil with a 60° slope. (Dimensions in mm).

[16] W. Herz, H. Katheder, H. Krauth, G. Nöther, U. Padligur, K. Rietzschel, F. Spath, L. Siewerdt, M. Süßer, A. Ulbricht, F. Wüchner, G. Zahn, Design and Process Engineering of the Karlsruhe Toroidal Coil Test Facility TOSKA. Tenth International Cryogenic Engineering Conference, Otaniemi, Finland, 31 July - 3 August 1984.

7. Cooling considerations

7.1 Twin facility

The cooling system of the Twin facility was designed under the following constraints which are similar to those of the cluster and solenoid configuration already described in the first report [1]:

- allow flexible helium mass flow and pressure independent of the refrigerator system,
- model coils, LCT coil case and support structure should be cooled at a temperature of 3.5 K,
- the LCT coil winding should be cooled independently of the model coil at a temperature level of 1.8 K, using the existing LINDE-refrigerator system,
- avoid a disturbance of the refrigerator system during quench or dump of the superconducting coils,
- helium losses during quench and dump have to be kept as low as possible,
- use the existing TOSKA facility and Linde refrigerator system for subcooling as much as possible,
- a new He I refrigerator system has to be installed for the TWIN test with adequate cooling power to perform the tests in a safe and reliable way.

Using this conditions and good experiences with secondary cooling loops already mentioned in the first report a cooling system was proposed for the TWIN arrangement as shown in Fig. 7.1-1.

7.2 Single coil test of the EU-LCT coil at 1.8 K

In this test, the entire cryogenic system including the new refrigerator, transfer lines, control cryostat with He-pumps, valve box and control system will be extensively pretested.

The EU-LCT coil winding was stably and reliably operated in Oak Ridge within a mass flow range of 30 g/s to 150 g/s. For the TOSKA Upgrade operation a mass flow of 50 g/s was chosen for the cooling of the LCT coil winding at 1.8 K. This is a relatively high mass flow compared to the mass flow of 15 g/s, required for removal of the heat input (30 W). Up to now it is known that a stable operation and helium flow distribution is possible with a flow rate of 50 g/s. During

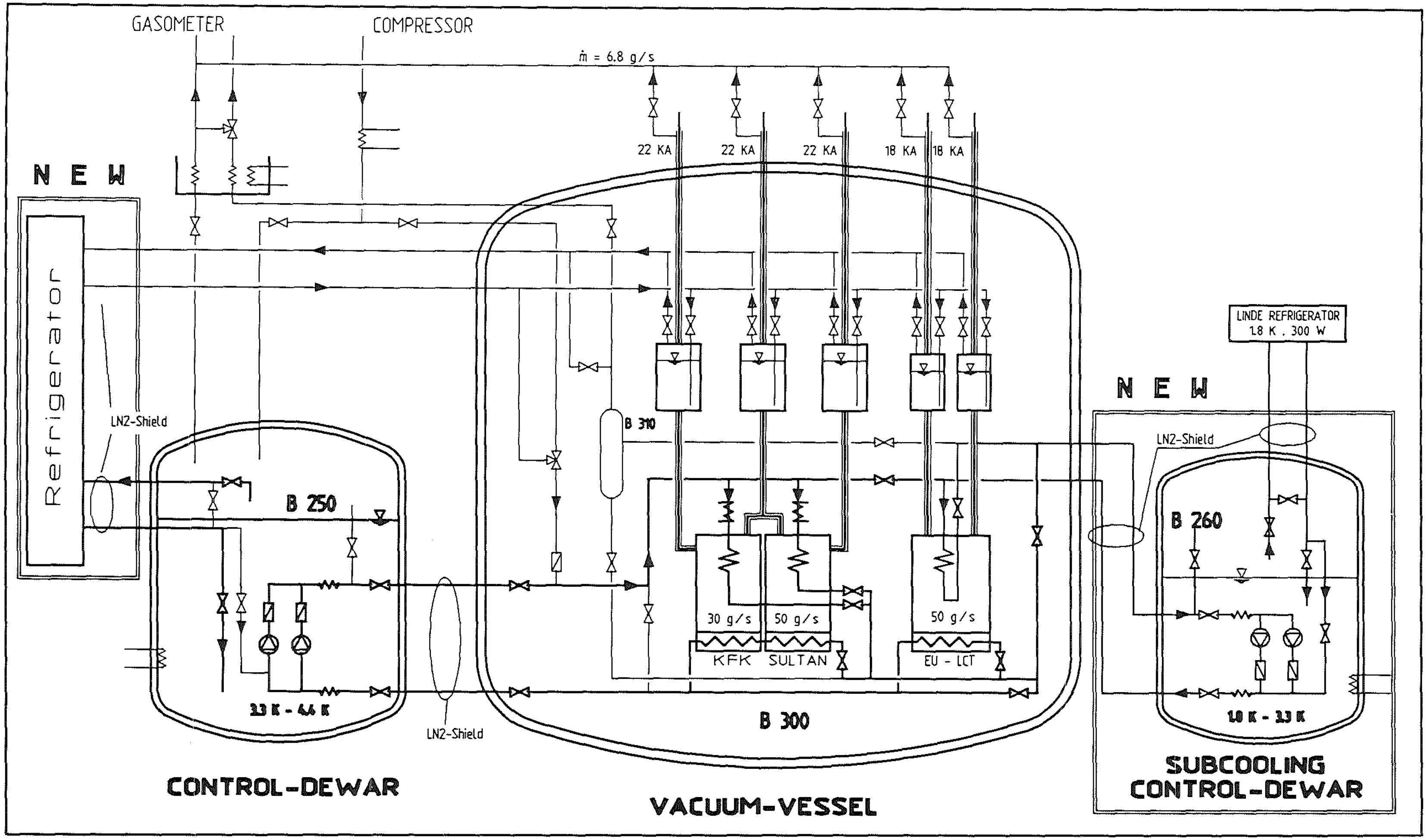

Fig. 7.1-1: Cryogenic system of the Twin configuration

operation the flow should be reduced to find out the minimum requirement of the LCT coil.

The constraints "use as much as possible the existing facility and design a flexible facility" which can be partly installed in parallel to the POLO project lead to this solution with a relatively large control cryostat and long transfer lines. A design without these contraints would be much smaller and the control cryostat close to the coil or if possible in the same vacuum vessel with short transfer lines.

7.3 Pumps for subcooled forced flow Helium

For circulating the He II in the secondary loop and through the LCT coil winding pumps are required if the mass flow exceeds the helium flow of the LINDE refrigerator (20 g/s). In order to find out the most suitable circulating device for large scale applications and also for reliability reasons a mechanical and a fountain effect pump (FEP) will be installed in parallel into the He II system of the TWIN facility.

7.3.1 Fountain effect pumps

The use of superfluid helium (He II) as coolant offers the possibility to operate the forced flow secondary loop with so-called fountain effect pumps. Such pumps have no moving mechanical parts. They can be operated in self-sustained mode where the helium convection is driven by the heat load of the coil and transfer lines. Thus such coolant loops promise to work with similar reliability as buoyancy driven natural convective loops but with the difference that the fountain effect can provide much higher pressure heads of up to $5 \cdot 10^4$ Pa.

For the use of such FEP's, however, it is necessary that the parameters of the loop (flow impedance and heat load) are compatible with the operational characteristic of the pump [17]. A respective calculation of the LCT coil proves that it is optimally suited. The presse drop may be approximated by $\Delta p \approx 8 \cdot 10^6 \dot{m}^2$, e.g. $2 \cdot 10^4$ Pa pressure drop at $50 \cdot 10^{-3}$ kg/s of flow rate!

Fig. 7.3-1 is a schematic of the proposed cooling system. The pump is immersed into the pool of saturated He II where it can be operated in parallel with mechanical pumps to be used for redundancy. The main heat load of the coil will be the conductive load from the 5 K case to the outermost pancakes (5 W on each double pancake) and thermal load by the current leads (≈ 20 W). The total load of 30 W will produce a total flow rate of 23 g/s, equally distributed to all 28 parallel channels of the coil. For this flow rate the peak temperature at the outlet of the outermost pancake will be 2.7 K. The He II with 1.8 K is fed into the high field region and the transition to He I is expected to be at positions where the magnetic field is decreased by about 50 %. This operational mode is expected to provide sufficient safety margin.

Such self-sustained FEP's can tolerate appreciably higher flow independances. Even for a very conservatice assumption with a five times higher pressure drop in the total loop, the 30 W heater power would induce a flow rate of 15 g/s. This is sufficient to operate the coil with about 3.3 K at the outlet of the outermost pancake and the He II/He I transition will be at a position where the field is decreased by about 30 %. In Fig. 7.3-1 are also shown the temperatures at different positions of the loop with those operational parameters. Additional safety margin can be provided by forcing more helium flow through the outermost channels. One option is to use the valves which are installed in the supply headers of the LCT coil. The other option is to feed additional power into the high temperature branch of the loop. With an additional power of 30 W the flow rate will be increased again to about 23 g/s and the peak temperature becomes 2.7 K but the pressure drop increases to $2.1 \cdot 10^4$ Pa.

Such pumps can be scaled from present results obtained from experiments done with small size pumps [18]. Their operational characteristics are well understood. Development and test of the full size pump is part of NET Task M15.

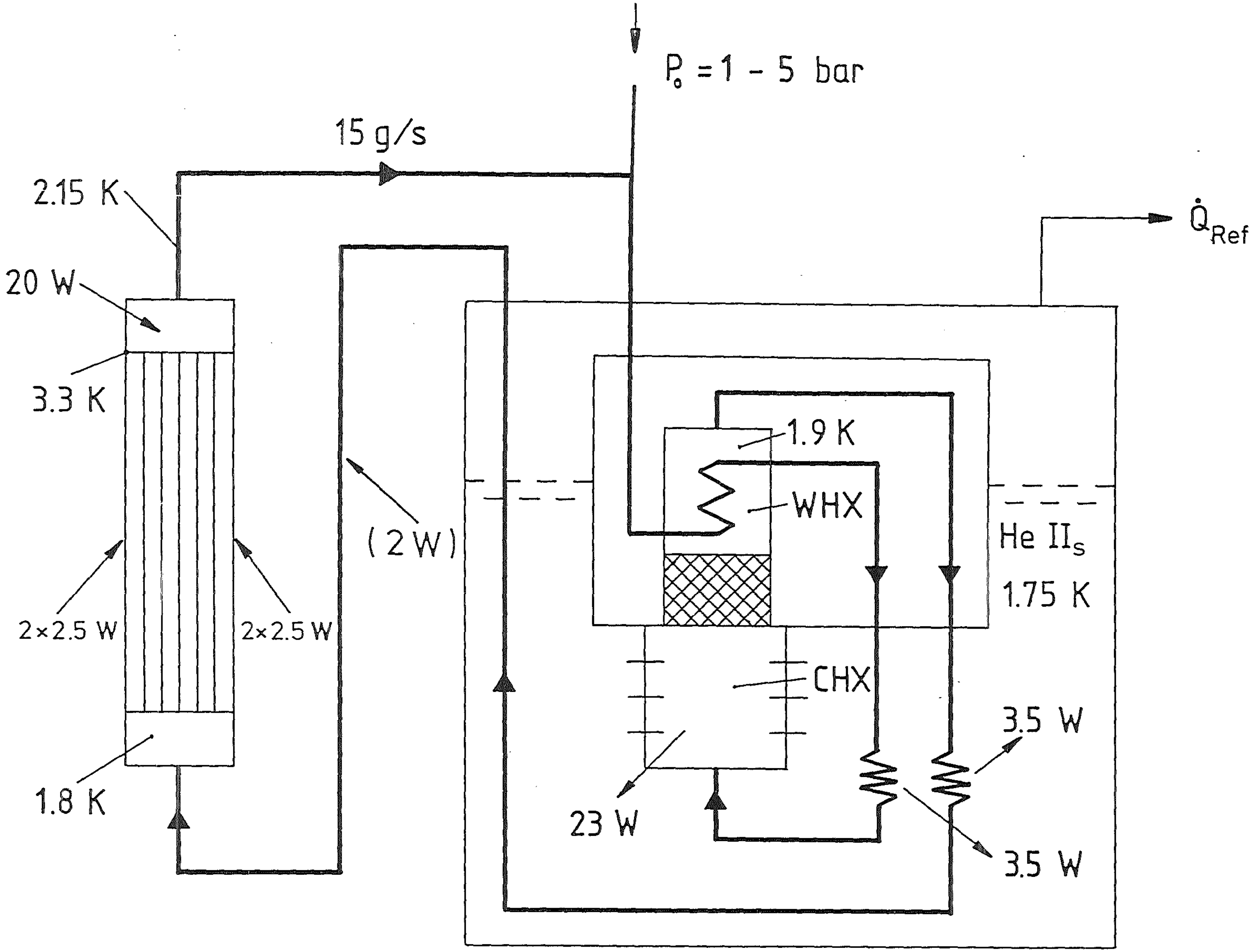

Fig. 7.3-1: Scheme of the coolant loop with a self-sustained fountain effect pump for the operation of the LCT coil with 1.8 K inlet temperature. (WHX = Warm Heat Exchanger, CHX = Cold Heat Exchanger).

7.3.2 Mechanical pumps

For the LCT coil test at KfK a three cylinder piston pump was developed, tested and successfully operated during the domestic coil test. This pump was designed for a mass flow of 150 g/s and a differential pressure of 3 bar. Now only 50 g/s and 0.4 bar are required. Nevertheless this pump can be used with a low efficiency. An optimized pump for the test will de developed together with industry.

7.4 Cooling considerations of the TWIN arrangements

The cooling system of the TWIN configuration is similar to the 1.8 K option of the cluster configuration described in our first report [1]. In the TWIN arrangement the helium mass flow is reduced in the 3.5 K loop to 70 g/s and in the 1.8 K loop to 50 g/s. The pressure drop of the model coils is reduced to 0.75 bar and in the 1.8 K loop to 0.2 bar. In addition, the number of current leads is reduced to 5 and consequently the total cooling power in the three different cooling circuits is reduced to about 340 W at 4.5 K, 540 W at 3.5 K and 150 W at 1.8 K. The simplified flow diagram of the TWIN configuration is shown in Fig. 7.1-1 valid for all three arrangements: TWIN adjacent, inserted upright and inserted with 60 degrees slope. The cooling power requirements are in Table 7.4-1.

The cooling system is designed for cool-down and warm-up of all coils with the new refrigerator by mixing warm and cold helium in a three way valve. A standby operation and an operation with reduced magnetic field and 3.5 K cooling of the LCT coil winding is also possible. The required 4.4 K equivalent cooling power for the TWIN configuration is 1.7 kW. This is lower than the cooling power of the solenoid configuration (2.8 kW) and the cluster configuration (2.6 kW) but exceeds still the cooling capacity of the existing refrigerators (600 + 400) W. Consequently a new refrigerator is necessary.

Table 7.4-1: Cooling conditions of the TWIN configurations

	Model coils		LCT-EU	Total	
	ATC	ITC		ATC	ITC
Coil					
Cooling length [m]	258	96	250		
No. of pancakes per coil	7 x 2	9 x 2	7 x 2		
Mass flow rate per cooling channel [g/s]	5	5	3.57		
Mass flow rate per coil [g/s]	70	90	50		
Inlet pressure [bar]	6	6	~ 2		
Pressure drop (coil and transfer lines) [bar]	0.75	0.5	0.2		
He inlet temperature [K]	3.5	3.5	1.8		
He outlet temperature [K]	3.9	3.7	1.97		
Pumping power ($\Delta p = 0.75/0.2^*$ bar, $\eta = 0.5$) [W]	70	60	14	70/14*	60/14*
Heat load [W]	10	20	10	20/10*	20/10*
Case					
Surface [m2]				134	134
Heat load [W]				145	145
Mass flow rate [g/s]				60	60
Current leads					
Warm gas flow rate [g/s]				6.7	6.7
Refrigeration power at T = 4.5 K level [W]				210	204
Refrigeration power at T = 3.5 K level [W]				15	15
Refrigeration power at T = 1.8 K level [W]				20	20
Facility					
Dewar, valves, at T = 4.5 K level [W]				40	40
pumps, transfer lines at T = 3.5 K level [W]				160	160
at T = 1.8 K level [W]				70	70
Calc. total cooling power					
at T = 4.5 K level [W]				250	244
at T = 3.5 K level [W]				410	400
at T = 1.8 K level [W]				114	114
Cooling power with					
a safety margin of 30% at T = 4.5 K level [W]				325	317
to be installed at T = 3.5 K level [W]				533	520
at T = 1.8 K level [W]				148	148

* values for 1.8 K loop

[17] A. Hofmann, A study on nuclear heat load tolerable for NET/TF coils cooled by internal flow of helium II, KfK Nr. 4365 (1988).

[18] A. Hofmann, A. Khalil and H.P. Krämer, Operational characteristics of loops with helium II flow driven by fountain effect pumps. Adv. Cryog. Eng. (Plenum Publ. Corp.). Vol. 33 (1988) 471-478.

8. Costs estimate

The costs of the TWIN configuration are estimated on the same base (LCT coil and the POLO model coil) as the costs in the first report [1].

Average specific manufacturing costs of 460 DM/kg have been evaluated for large superconducting coils. Another uncertainty is still a different design for components (e. g. joints) and the handling of the brittle Nb_3Sn conductor.

The costs for material, manufacturing, pretests, detail design, development of components and calculations but <u>not the costs of the conductor</u> and installation into the facility are included in the following approximate costs of the model coils. The conductor development and manufacturing costs are quoted in task TFI (M5) and therefore not in this estimation. Only the amount of conductor necessary for the model coils is included in the tables for comparison.

The facility costs are estimated on the base of the TOSKA- facility and include the installation at KfK, pretests, and acceptance tests.

The operating costs contain mainly electricity, cooling water, helium losses, maintenance and repair but not manpower and interests.

8.1 Costs of the Twin configurations

The costs and manpower requirements for facility modification and carrying out the tests are represented in Tables 8.1-1 and 8.1-2. The values there are valid for all three twin configurations except in case of the inserted upright model coils where the support structure is less by 400 TDM.

For comparison, the costs and conductor quantities for all configurations studied are summarized in Table 8.1-3. It is obvious that the insert configuration requires the lowest investment and conductor quantities but it has to be clarified whether a bending radius of 0.81 m is acceptable or not.

Table 8.1-1 Approximate Costs and Manpower Requirements for the Facility Modifications of the Twin-Test Version 1.8 K.

	Quantity	Costs Mio. DM		Manpower				
		Cap.*	Con.**	1st year	2nd year	3rd year	4th year (1/2 year)	Man x a
Goal				1989	1990	1991	1992	
<u>Facility</u>								
Design								
Coordination				1	1	1	1 x 0.5	3.5
Transfer Lines and Piping		1.3	0.5					
He-Pumps	2 pcs	0.2	0.1	1	1	1	1 x 0.5	3.5
Vacuum Pump System		0.1	0.1					
Vacuum Vessel Modification		0.2	0.2					
Current Leads	5 pcs	0.3	0.1	1	1	1	1 x 0.5	3.5
Support Structure and Helium Cylinder		0.6	0.4	1	1	1	1 x 0.5	3.5
Support Structure EU-Coil		0.8	0.2	1	1	1	1 x 0.5	3.5
Control-Dewar B 260		0.3	0.1					
Pretests and Operation	0.3 a		0.7				7 x 0.5	3.5
Support Staff				2	3	2	5 x 0.5	9.5
<u>Power Supply</u>								
22 kA/20 V - Power Supply	220 kW	0.3	0.1	1 x 0.5	1	1	1 x 0.5	3
22 kA/ 5 kV Switch and Dump Systems		0.3	0.2					
22 kA/2 x 4.5 kV Switch and Dump Systems		0.2	0.1	1 x 0.5	1	1	1 x 0.5	3
Support Staff				2 x 0.5		2 x 0.5	2 x 0.5	3
<u>Diagnostic</u>								
Data Acquisition System		0.2	0.3	1 x 0.5	1	1	1 x 0.5	3
Software				1 x 0.5	1	1	1 x 0.5	3
Control System		0.3	0.2	1 x 0.5	1	1	1 x 0.5	3
<u>Total Costs</u> Capital Costs (Mio. DM)*		5.1		1.4	2.0	1.6	0.1	
<u>Total Costs</u> Consumables and technical Services (Mio. DM)**			3.3	0.2	1.2	1.2	0.7	
<u>Total Manpower Requirements</u> (MJ)				10.5	13	13	24 x 0.5	48.5

Table 8.1-2 Approximate Costs and Manpower Requirements for Installation of the Test Coils and carrying out the Test

	Time	Costs Mio. DM		Manpower			
		Cap.*	Con.**	4st year (1/2 year)	5nd year	6rd year	Man x a
Goal				1992	1993	1994	
<u>Installation and Pretest of the Model Coils</u>	1 year	0.1					
Coordination				1 x 0.5	1 x 0.5		1
Representative of the Model Coils				4 x 0.5	4 x 0.5		4
Cryogenic System				2 x 0.5	2 x 0.5		2
Diagnostic				3 x 0.5	3 x 0.5		3
Support Structure and Helium Cylinder				1 x 0.5	1 x 0.5		1
Power Supply, Pretest Switch and Dump System				2 x 0.5	2 x 0.5		2
Support Staff			0.8	10 x 0.5	10 x 0.5		10
<u>Test of the Model Coils</u>	1 year	0.1					
Coordination					1 x 0.5	1 x 0.5	1
Representative of the Model Coils					6 x 0.5	6 x 0.5	6
Cryogenic System					2 x 0.5	2 x 0.5	2
Diagnostic					3 x 0.5	3 x 0.5	3
Power Supply, Switch and Dump System					2 x 0.5	2 x 0.5	2
Operation			1.5		7 x 0.5	7 x 0.5	7
Support Staff					7 x 0.5	7 x 0.5	7
<u>Result Evaluation</u>	0,5 year	0.1					
Coordination						1 x 0.5	0.5
Representative of the Model Coils						2 x 0.5	1
Cryogenic System						1 x 0.5	0.5
System Performance						1 x 0.5	0.5
Magnet and FEM-Calculation					1 x 0.5	2 x 0.5	2.5
Support Staff						4 x 0.5	2
<u>Total Costs</u> Capital Costs (Mio. DM		0.3		0.1	0.1	0.1	
<u>Total Costs</u> Consumables and technical Services (Mio. DM)			2.3	0.6	1.0	0.7	
<u>Total Manpower Requirements</u> (MJ)				11.5	26	20.5	58

Table 8.1-3 Comparison of conductor quantities and costs for facility modification and tests (operating temperaturs of the configurations are given in round brackets in row 1)

Configuration	Conductor Quantity [m]	Capital [Mio. DM]	Consumables [Mio. DM]	Installation and Tests [Mio DM]
Cluster (3.5 K)	3500 TF	5.4	3.3	2.0
Solenoid (3.5 K)	4650 TF and 1050 OH	5.2	2.9	3.0
Twin ATC (1.8 K)	3600 TF	5.4	3.3	2.3
Twin ITC (1.8 K)	1550 TF	5.0	3.3	2.3

all costs without manpower costs and investment for cooling power

9. Time Schedule

A detailed time schedule for both TWIN configurations is shown in Table 9.1. The schedule is based on the following assumptions:

- a contract for facility modification and manufacturing of the 1.8 K part can be placed in 1988,

- the final version of the test rig has to be decided in June 1989,

- the industrial fabrication of TF conductor prototype lengths will be started in June 1989,

- the POLO tests have to be finished in December 1990 and the facility is available for modification in January 1991.

Any delay of these actions would result in a delay of the test and test results.

Table 9.1 Time schedule for the TWIN configurations.

Project Year		1	2	3	4	5	6
Goal	88	89	90	91	92	93	94
TOSKA-Facility TFU 1							
Design of facility	******	******	***				
Design of LCT coil reinforcement	***	***					
Reinforcement of the LCT coil		***	***				
Manufacturing of 1.8 K part		****					
Installation and pretest of 1.8 K part		**	***				
Manufacturing of components		**	******				
Modification of facility				****			
Installation of LCT coil				**			
Test of LCT coil at 1.8 K					***		
Power supply		**	******	******			
Data acquisition system		******	******	******	******	***	
Refrigerator	******	******	******	******			
NET-model coils TFP							
Design and manufactur-ing of conductor	******	******	******	******			
Design and manufactur-ing of model coils		***	******	******	***		
TF-model coil operation TFU 2							
Installation of model coils and support structure					**	***	
Operation						***	****
Result evaluation							****

10. Test programme for the TOSKA Twin model coil test

The detailed test programme is discussed in the first report about NET model coil testing [1]. Therefore only general aspects are repeated here.

The model coil test program should verify the manufacturing process and conductor and coil performance of the NET-TF coil designs. It should prove the feasibility of the entire conductor and coil manufacture process including coil termination, winding, insulation and vacuum impregnation of double pancakes. The conductor and coil performance should be verified not only by measurement of the steady state nominal operating characteristics but also for mechanical and AC-behaviour.

Testing of the Toroidal Field Coils should specifically include:

- standard operation - energize coils to the operating current to achieve the nominal peak field at the conductor (16 kA, 11.4 T). Measure steady state value of pressure drop, flow rate, helium inlet and outlet temperatures, pancake joint and termination resistance and heat loads. This standard operation (16 kA in model coil and simultaneously 11.4 T at the coil) is only possible in the TOSKA Twin test with about 6 - 7 km of conductor. This amount of conductor length is not reconcilable with those foreseen by NET for model coils.

- stress/strain - because of the size and geometry of the test configuration it is difficult to simulate the actual operating stress/strain of the NET coils. Therefore additional external mechanical loads should be applied if possible and if needed, to approach these conditions of transverse, hoop and shear stresses. Strain measurements on the outer surface of the coil should be made to estimate the global winding pack mechanical characteristics.

- quench tests - the dynamic behaviour of the coils during quenching should be studied to determine the He temperature and pressure, and pressure drop, and coil voltages as a function of time for different operating currents, dump delay times, and dump time constants, and also the quench propagation velocity. Proposed quench detection systems have to be developed and tested on these coils.

- AC-loss - an AC field should be applied from an external field source while the coil is energized at the standard condition. The goal is not to perform an exhaustive ac loss test but to verify the predicted performance.

- critical current and temperature - the operating margins should be determined either by individually raising the current in each coil until a predetermined voltage is measured or by individually raising the inlet helium temperature at constant current to reach the normal transition point; this is the determination of the magnet load line.

These kind of tests should deliver results needed for the construction of NET TF coils. Information on the last item will be compared with those obtained from short sample tests (e.g. SULTAN).

11. Technical comparison of the test arrangements

The test arrangements presented in this report will be compared to each other and with the cluster test arrangement C6 from [1]. Table 11.1 shows the main characteristics of the model coils for the Cluster and the Twin arrangement with adjacent or inserted model coils. This table contains also the main characteristics of the Solenoid configuration S 3 already discussed in [1]. However, main emphasis of this technical comparison is given to the Cluster and the Twin configuration, because the task of this report is mainly to elaborate the differences between both.

The most important difference is that the ITC coils have a reduced bending radius of 0.81 m compared to 1.0 m in case of Cluster and adjacent arrangement. The reduction of the bending radius has a large impact on the coil characteristics. However, it must be decided whether the reduction of the minimum bending radius to 0.81 m and the resulting degradation of the current density of Nb_3Sn due to the higher strain is acceptable or not.

A common feature of all model coils is the winding technique: double pancake and two conductors in hand, a technique which was verified by the EURATOM LCT coil [3]. All model coils should be operated up to 22 kA instead of the NET operation current of 16 kA. The reason for that is to avoid excessive conductor lengths or costs.

Comparing Cluster and adjacent model coils there is really no big difference neither in geometry nor between the electromagnetic data. The advantage of the adjacent arrangement consists in the fact to avoid of the third coil, which was used in the Cluster facility. Therefore more room for installation is available. Comparing the numbers in Table 11.1, it must be mentioned that the KfK and SULTAN model coils have to be compared together with the ATC model coil. For the sake of simplicity for the calculations of the ATC only one current density was chosen. Really comparable geometric characteristics are radial winding thickness, average winding radius, average turn length, and average conductor length. The axial winding width and the total conductor length of the KfK and SULTAN model coils have to be added up for comparison. Similar considerations are valid for other values. As a conclusion of the comparison, no significant difference can be found between the KfK and SULTAN model coils of the Cluster

Table 11.1: Comparison of model coil characteristics for the Cluster Test Facility C6 [1], Solenoid Facility S3 [1], the Twin Test with adjacent and inserted model coils. (MC = Model Coil)

		CLUSTER C6		SOLENOID S3			TWIN		
	Unit	MC KfK	MC SULTAN	MC KfK	MC OH	MC SULTAN	ATC MC	ITC MC (upright)	ITC MC (60° slope)
Model coil current Current density	kA kA/cm2	22 3.308	22 2.958	22 3.308	50 3.003	22 2.958	22 3.308	22 3.308	22 3.308
Number of pancakes Number of layers per pancake Total number of turns		2 x 3 34 204	2 × 5 22 220	2 × 5 30 300	2 × 4 16 128	2 × 7 20 280	2 × 7 32 448	2 × 8 16 256	2 × 9 16 288
Inner radius, r_i	m	1.0	1.0	1.0	1.0	1.0	1.0	0.81	0.81
Radial winding thickness Axial winding width Average winding radius	m m m	0.595 0.228 1.2975	0.5896 0.277 1.2948	0.525 0.38 1.2625	0.5328 0.4 0.2664	0.536 0.3878 1.268	0.56 0.532 1.28	0.28 0.608 0.95	0.28 0.684 0.95
Average turn length Average conductor length per pancake (= cooling length)	m m	8.15 277	8.14 179	7.94 238	7.98 127	7.97 160	8.05 258	5.97 95.5	5.97 95.5
Total conductor length (not including spare lengths for fabrication and joints (about 10 %))	m	1664	1790	2380	1019	2231	3603	1528	1719
Winding cross section Winding volume Estimated winding weight (ρ about 7 t/m^3)	m x m m^3 t	0.13566 1.11 7.8	0.16332 1.33 9.3	0.2 1.584 11.1	0.213 1.7 11.9	0.208 1.66 11.6	0.298 2.396 16.8	0.17 1.02 7.0	0.19 1.14 8.0
Total coil current Ampère-meters	10^6A 10^6Am	4.488 36.608	4.84 39.38	6.6 53	6.4 51	6.16 49	9.856 79.34	5.632 33.62	6.336 37.82
Stored Self-Energy	MJ	34	38	67	40	58	138	32	39
Operating temperature (Inlet)	K	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
B_{max} at the winding of MC for 13 kA in EU-Coil	T	12.1	12.0						
				12.27	11.62	11.54			
B_{max} at the winding of MC for 18 kA in EU-Coil							11.85	11.6	11.46

C6 and the ATC model coils with respect to geometric and electromagnetic properties.

Table 11.2 shows a comparison of the total cooling power for the Cluster C6 configuration, the ATC and ITC, and also for the Solenoid configuration. It must be mentioned that the total cooling power for ATC and/or ITC is reduced to about 1.7 kW compared to 2.6 kW for Cluster C6 and the Solenoid, but the 1.8 K part of the Linde refrigerator is necessary.
The comparison of the ATC and the ITC shows the big impact of the reduced bending radius. Much smaller model coils are the result. The required conductor length of the arrangement with inserted coils is only half of that for the adjacent test configuration and consequently also the Ampère meters.

Table 11.2: Comparison of the total cooling power

	Cluster Config. C6, Version 3.5 K			Solenoid Configuration S3			ATC				ITC			
	Q[W] 3.3 K*	Q[W] 4.5 K	ṁ[g/s] 4.5-300K	Q[W] 3.3 K*	Q[W] 4.5 K	ṁ[g/s] 4.5-300K	Q[W] 1.8 K*	Q[W] 3.3 K*	Q[W] 4.5 K	ṁ[g/s] 4.5-300K	Q[W] 1.8 K*	Q[W] 3.3 K*	Q[W] 4.5 K	ṁ[g/s] 4.5-300K
<u>Background Coil</u> Heat load Pumping power	 160 140						 10 14	 65			 10 14	 65		
<u>Test Coils</u> Heat load winding Heat load case Pumping power	 20 80 110			 30 80 117				 20 80 70				 20 80 60		
<u>Current Leads</u> Twin 102 kA/Cluster 105 kA (0,065 g/s kA + 2 W/kA	25	210	6.8	20	332	10	20	15	210	6.7	20	15	204	6.7
<u>Facility</u> Dewar, valves, transfer lines, pumps	160	50		210	50		70	160	40		70	160	40	
Calculated cooling power Cooling power with a safety margin of 30%	695 904	260 338	6.8 8.8	457 594	382 496	10 13	114 148	410 533	250 325	6.7 8.7	114 148	400 520	244 317	6.7 8.7
Cooling power 4.4 K equivalent		~ 2,6 kW		~ 2,7 kW				Linde Refrig.	~1,7 kW		Linde Refrig.		~ 1.7 kW	

*Temperature in the Control Dewar

Table 11.3 contains the operating conditions for the Cluster C6, the Solenoid S3, and the ATC model coils. The most evident change is the 1.8 K operation as already mentioned in [1] of the EURATOM LCT coil with an enhanced current of 18 kA in ATC.

The removal of the Swiss coil has serious and severe consequences for the force distribution and reveals the main and decisive difference between both coil test arrangements using the LCT-coil. In the Cluster C6 the centering force is - 68.7 MN for the model test coils (37.5 MN for EU-coil and 31.2 MN for the Swiss coil). In principle one can find only by parallel moving a position of the three coils where each coil has a resulting zero centering force. This is also true for the adjacent test, where actually the centering force is 18.5 MN. However, the out-of-plane force behaves completely different. In the Cluster C6 the model coil is nearly out-of-plane force free. However in the adjacent arrangement the model coil experiences the full out-of-plane force of 115 MN. The EU LCT coil experienced already an out-of-plane force of 26.6 MN in the LCT test [3]. Considering now 115 MN to be balanced an effective mechanical support system has to be constructed for ATC. In the Cluster C6 only 87 MN of the EU LCT have to be balanced.

The total stored energies in both test arrangements are not surprisingly almost equal. However, the stored energy of the EU LCT coil is in the ATC almost twice the value of the Cluster C6. This requires special care for the safety discharge circuit of the coil.

Compared to Cluster C6 where the rotation angle is 14 degrees between model coils and EU LCT coil, the ATC has only 9 degrees. This together with the fact that only two coils have to be installed into the TOSKA vacuum vessel allows much more space and freedom for installation work, maintenance and repair.

The comparison of the stresses for the model coils of Cluster C6 and ATC show big differences, but for ATC a case with thickness of 25 mm, resp. 50 mm was taken into account. Therefore a direct comparison is not possible. A variation of the coil case thickness allows the adaption of the stresses in the model coils to the required NET values, but only to some extent. Stresses in the EU LCT coil were calculated analytically for the Cluster C6 with a simplified geometry. For the ATC the stresses of the LCT coil has to be analyzed together with the reinforcement construction of the coil.

Table 11.3: Comparison of the main operating characteristics of the Cluster Test Facility C6 [1], Solenoid Test Facility [1], and the Twin Test with adjacent NET model coils. (Operating conditions for the Swiss coil are omitted, because this coil is not used in the Twin Test). (MC = Model Coil)

	Units	CLUSTER C6		ATC		SOLENOID S3	
		MC (KfK/SULTAN)	EU-COIL	MC	EU-COIL	MC (KfK/SULTAN)	MC OH
Minimum bending radius for MC	m	1.0	not important	1.0	not important	1.0	1.0
Temperature (Inlet)	K	3.5/3.5	3.5	3.5	1.8	3.5	3.5
Conductor current Total coil current	kA MA	22 4.488/4.84	13 7.644	22 9.856	18 10.584	22 6.6/6.16	5.0 6.4
Magnetic field at reference point of winding pack	T	12.1/12.0	8.3	11.69	10.33	12.27/11.54	11.62
Force in x-direction (centering force) Force in y-direction (out-of-plane force)	MN MN	-68.7 1.5	37.5 -86.6	-18.5 115.2	18.5 -115.2	0 0	0 0
Stored self energy Total stored energy	MJ MJ	34/38 512	134	138 507	253	67/58	40
Rotation angle to x-direction	degree	0/0	14	0	9	0	0
Case thickness	mm	0/0	50	25 50	50	0/0	0
Hoop stress Axial pressure Radial pressure Shear stress	MPa MPa MPa MPa	310.7/309.9 -27.4/-26.3 -65.1/-64.3 -26.8/-28.8	- 435* 60* 35*	210 170 -48 -52 -62 -82 -14 -11	x	153/118 -50.2/43.4 -63/50.3 -15.5	143 -44.3 -51.3

* obtained by analytic calculation with a simplified geometry

x has to be investigated together with the reinforcement of the EU-coil

o values for the Swiss coil are similar

Two test arrangements were investigated with model coils inserted into the bore of the EU LCT coil. Table 11.4 compares both arrangements. The EURATOM LCT coil has to be operated at 1.8 K in order to give the favourable features of this test arrangement. Comments for the EU-LCT coil given to the numbers in the previous Table 11.2 are also valid for Table 11.3.

The model coils for both arrangements are very similar. The 60° slope solution has 9 double pancakes instead of 8 for the upright (90°) solution, but the same radial thickness (see Table 11.1). This results in a higher coil current and higher stored energy.

A main difference is seen for the force distribution in both arrangements. It should be mentioned again, that the model coil in the 60° slope solution is moved by 10 cm in y-direction from the common coil center ($y = 0$). Only an x-component of the force exists in the upright (90°) solution. The movement from the common coil center causes a y-component of the force and the rotation creates a z-component. However, the magnitude of the force is much smaller than for the Cluster C6 and the ATC.

Table 11.4: Comparison of the main operational characteristics of the Twin Tests with inserted model coils. (MC = Model Coil).

	Unit	ITC upright coils		ITC 60° slope	
		MC upright (90°)	EU-coil	MC 60° slope	EU-coil
Minimum bending radius for MC	m	0.81	not important	0.81	not important
Temperature (Inlet)	K	3.5	1.8	3.5	1.8
Conductor current Total coil current	kA MA	22 5.632	18 10.58	22 6.336	18 10.58
Magnetic field at reference point of winding pack	T	11.40	8.00	11.28	7.55
Force in x-direction (centering force) Force in y-direction (out-of-plane force) Force in z-direction	MN MN MN	3.72 0.0 0.0	-3.72 0.0 0.0	1.8 -8.6 - 2.6	-1.8 8.6 + 2.6
Stored self energy	MJ	32	253	39	253
Total stored energy	MJ	356		356	
Case thickness	mm	50		50	
Hoop stress Axial pressure Radial pressure Shear stress	MPa MPa MPa MPa	166 70 95 9	x	x	x

x has to be investigated together with the reinforcement of the EU-coil

A qualitative comparison of the Cluster C6 and the Twin configurations ATC and ITC was undertaken with respect to facility modification, installation, and maintenance of the test assembly. The Cluster C6 is already discussed in [1]. Therefore, the emphasis is given to the Twin configurations.

Modifications of the existing vacuum vessel for the Twin configurations are necessary, but they are not too expensive, e.g. ports for the additional current leads have to be built in. It is not necessary to remove the vacuum vessel from the pit in the experimental hall in order to perform all the modifications. The vacuum vessel can stay at place and therefore it is not necessary to remove the already installed transfer lines. An enlargement of the LN_2-shield is not required. Only transfer lines to the new refrigerator have to be installed. A connection of the 1.8 K cooling loop to the existing refrigeration system is necessary for the 1.8 K operation of the EU LCT coil.

The support structure for the test arrangement is estimated to be difficult and expensive except for the inserted upright configuration. Appropriate regions on the casing of the LCT coil have to be searched (found) in order to provide supports to balance axial forces. Especially the existing cooling channels, Helium supply headers and the reinforcement of the LCT coil itself restrict the area for intercoil support. The reinforcement of the EURATOM LCT coil itself seems to be a difficult problem, even in the case of the inserted model coil with 60° slope the reinforcement has to be integrated into the casing of the model coil, not an easy task to perform.

Extensive installation work is required for the Twin configurations, the easiest in the inserted upright solution. A special problem is the conductor joining. Due to space restrictions it is difficult, but possible. Solutions are proposed in preceding chapters. The installation of a pulse coil seems to be questionable in all configurations, but a detailed investigation was not performed to elucidate the restrictions.

The maintenance of the test assembly seems to be feasible without major difficulties for all the considered Twin configurations. All in all, the Twin configurations are more favourable than the Cluster C6 configuration.

The next Table 11.5 shows the main test target values for field, current and stresses (see Table 2.1) for NET in comparison with the discussed test arrangements. Here, the values for the Solenoid S3 are also added, but not extensively discussed.

The primary guide during the numerical evaluation was the magnetic field level to be achieved in the test facility. The facilities fulfill the magnetic field requirements by NET. However the operation at the NET nominal current of 16 kA led to too high conductor lengths for both facilities. To stay within reasonable limits (given by M5) the current was rised to 22 kA. This is certainly an acceptable compromise from a technical point of view as short sample tests and pancake tests in SULTAN III [1] can be performed either at NET operating conditions (11 T, 16 kA) or/and at TOSKA-Upgrade conditions (11 T, 22 kA). These tests can deliver a solid, experimental basis for reliable extrapolation of data obtained from model coil tests in TOSKA-Upgrade to NET-operating conditions.

Comparing the stresses of NET-TF coils with stresses reached in the test arrangements for model coils big differences are seen. Axial stresses for NET are 140 MPa, but only half that value is reached in ITC with an upright model coil. Therefore an additional gadget for the stress simulation is indispensable. The radial pressure of 40 MPa for NET is surpassed in all test arrangements by a factor of 1.5 - 2.3. The NET hoop stress value of 140 MPa is also missed by a factor of 1.2 - 2.2, but the values can be adapted in certain limits by variation of the coil case thickness. The NET shear stress value of 30 MPa is almost reached by the model coils of the Cluster C6. Only half of that value can be attained in any of the Twin configurations. As discussed in [1] a rod can be applied to the model coils in order to enhance the shear stress values.

The last line gives again the minimum bending radii to point out the differences. The values in Table 11.6 alltogether show how the NET values are approached by the different test arrangements.

Table 11.5: Comparison of values required by NET and attainable values in the Cluster, Solenoid and Twin Configurations. (MC = Model Coil)

	NET		CLUSTER Configuration C6		TWIN Configuration			SOLENOID Configuration S3		
	TF- Coil	OH- Coil	KfK- Coil	SULTAN Coil	Adjacent MC	Inserted MC Upright (90°)	Inserted MC 60° slope	KfK-Coil	OH-Coil	SULTAN-Coil
Maximum Field [T]	11.4	11.5	12.1	12.0	11.85	11.6	11.46	12.27	11.62	11.54
Current [kA]	16	40	22	22	22	22	22	22	50	22
Axial Pressure [MPa]	140	100	27.4	26.3	48/52*	70		50.2	44.3	43.4
Radial Pressure [MPa]	40	10	65.1	64.3	62/82*	95		63	51.3	50.3
Hoop Stress [MPa]	140	200	310.7	309.9	210/170*	166		153	143	118
Shear Stress [MPa]	30	30	26.8	28.8	14/11*	9		15.5		
Minimum Bending Radius [m]	2.1	1.6	1.0	1.0	1.0	0.81	0.81	1.0	1.0	1.0

* first number for 25 mm thickness of coil case / second number for 50 mm thickness

12. Concluding remarks

In this report the test of the NET-TF conductor wound to model coils in the existing TOSKA facility is investigated. The magnetic field of the EURATOM LCT coil is used as background field. This Twin test will be really successfull if the EU LCT coil is used at still higher performance than experimentally proved in the LCT test. The behaviour of the LCT coil at higher currents (or higher fields) is studied. This high performance operation implies its 1.8 K operation.

Two principal test arrangements were investigated: a NET model coil adjacent to the EU LCT coil and a NET model coil inserted into its bore. The second test arrangement is only possible if the minimum bending radius is decreased to 0.81 m (from 1.0 m for the adjacent model coil). Advantages and disadvantages are discussed in detail in previous chapters.

At first a test of the EURATOM LCT coil at a temperature of 1.8 K up to the required operation limits of the coil has to be performed. This test should prove not only the operability of large forced flow NbTi-TF-coils at this temperature but can also show the possibility to use a conductor based on the principles of the already tested EURATOM-LCT-conductor for a NET-TF-coil backup solution with NbTi-conductors. This first test needs an 1.8 K cooling system. Also an LCT coil reinforcing structure has to be provided. It would be most favourable if the tests of the Nb_3Sn-NET-TF model coils would be defined as a common test arrangement together with the 1.8 K test of the EU LCT coil, because not only the reinforcing structure for the EU LCT coil itself but also the intercoil support structure of EU LCT coil and NET model coils could be designed together. Costs and manpower could be saved in that way.