Status of the Conductor Development for the Stellarator Wendelstein 7-X

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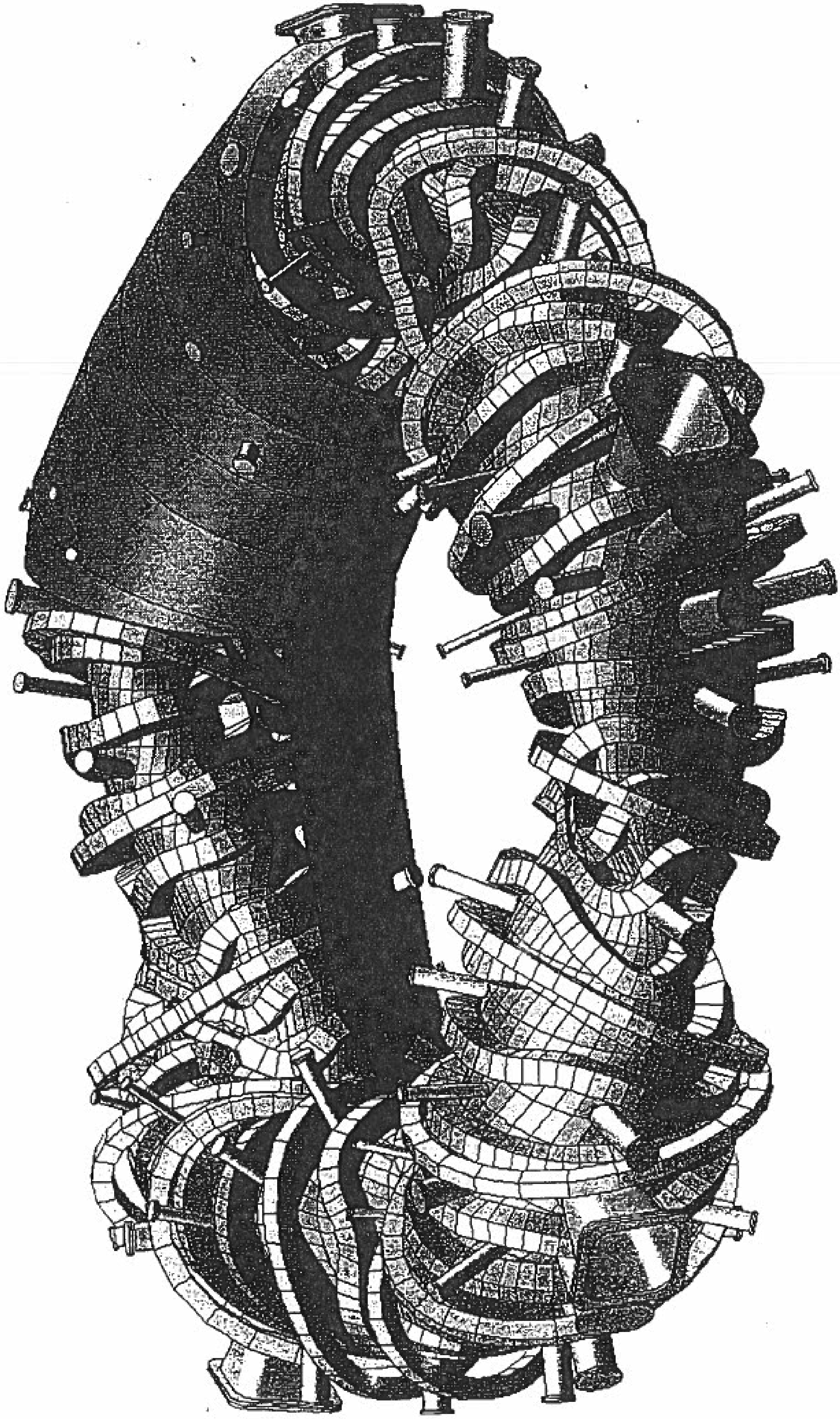
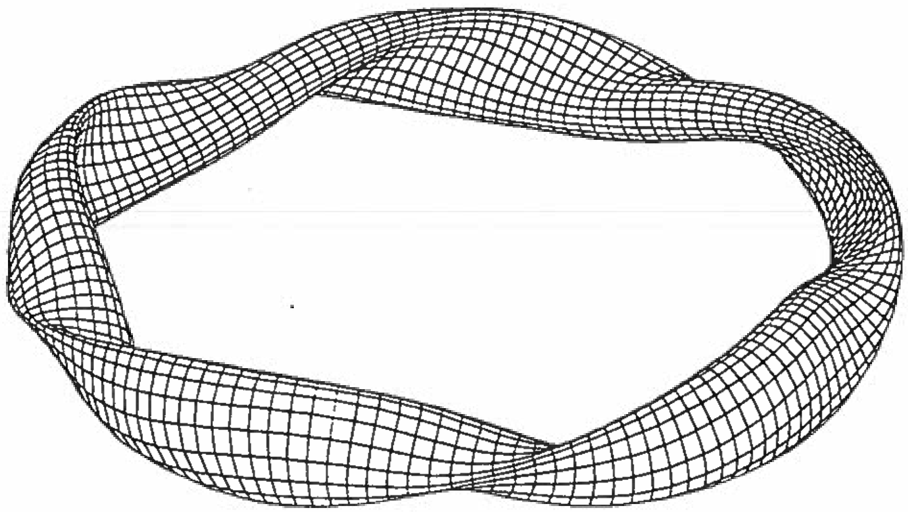
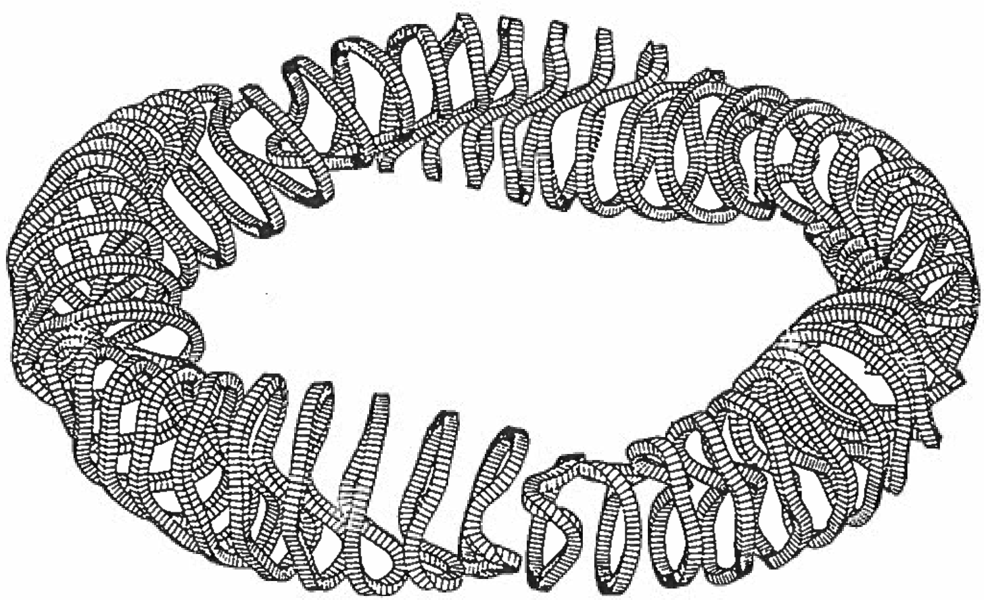






Introduction

- Magnet system of Wendelstein 7-X consists of 50 nonplanar and 20 planar coils

- Development steps:

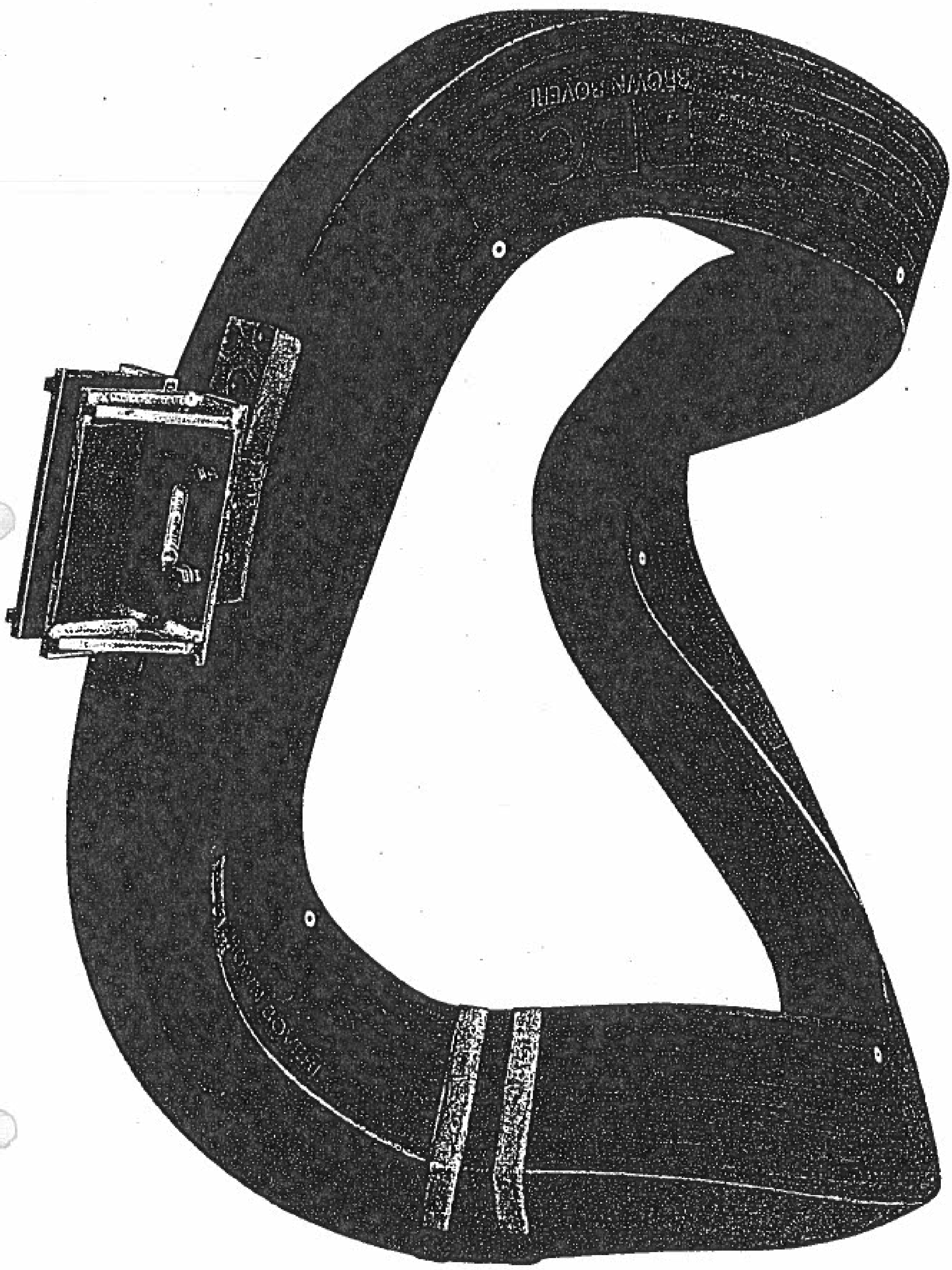
1. Development of a flexible conductor to be wound in a non-planar shape of a modular coil

2. Construction and test of a solenoidal model coil wound from one conductor length in order to test the electromagnetic and thermohydraulic behaviour

3. Construction and test of a demonstation coil of full size in order to prove the mechanical performance

Introduction (cont′d)

- Design philosophy for the coils is to use as much as possible the experience gathered during construction of the (copper-)coils for W 7-AS
- Main parameters are:
  - Maximum magnetic field B = 6 T
  - Coil current I = 16 kA
  - Coil dimensions are: about 3 m diameter and 31 cm x 28 cm cross section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Superconductor

- Required properties:

1. Good windability at a minimum bending radius of only 20 cm

2. Forced flow cooled NbTi/Cu cable within an aluminium alloy conduit

3. Staged cable (3 x 4 x 4 x 4) fabricated from commercially available strands

4. Co-extruded aluminium jacket around the cable

5. Al material from the 6000 series

Superconductor (cont'd)

- Degradation during fabrication of cable has been measured systematically
- Although stellarator uses a steady state magnetic field, AC losses occur
  - during plasma formation
  - during divertor sweeping if any
  - due to ripple of power supply
- Pressure drop and heater experiments have been done using a 1.4 m long conductor with copper strands

Superconductor cable data (LMI) for solenoidal test coil

- LMI has fabricated and delivered about 400 m of the conductor
- half of this length is used for the construction of a solenoidal model coil to be tested in the test facility STAR at KfK

Diameter of strand	0.55 mm
Diameter of filament	27 μ
Number of filaments	132
Filament twist pitch	25 mm
Number of strands	192
α	2.03
Coupling time constant (calculated)	65 ms
Operational current	16 kA
Critical current at $T=4.2$ K, $B=6$ T	31.6 kA
Helium void fraction	37.5 %

EUROPA METALLI - LMI spa
Head office: 50121 Florence, Borgo Pinti 99, (Italy)
Phone: (55) 47741 - Telex 571598 SMIFI I - FAX (55) 2478067
P.O. Box No. 349 Florence
Research Centre: 55052 FORNACI DI BARGA (Lucca) Italy
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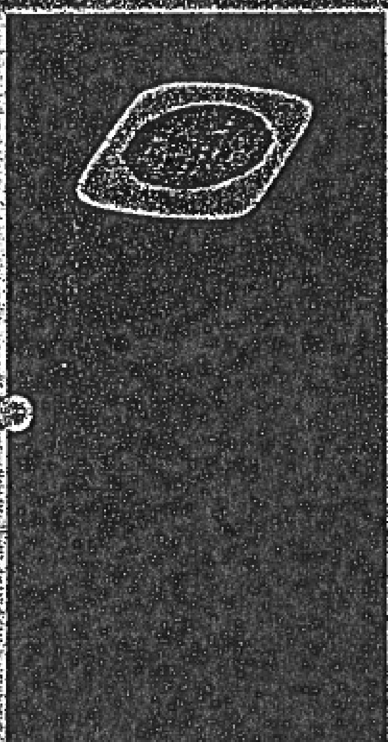
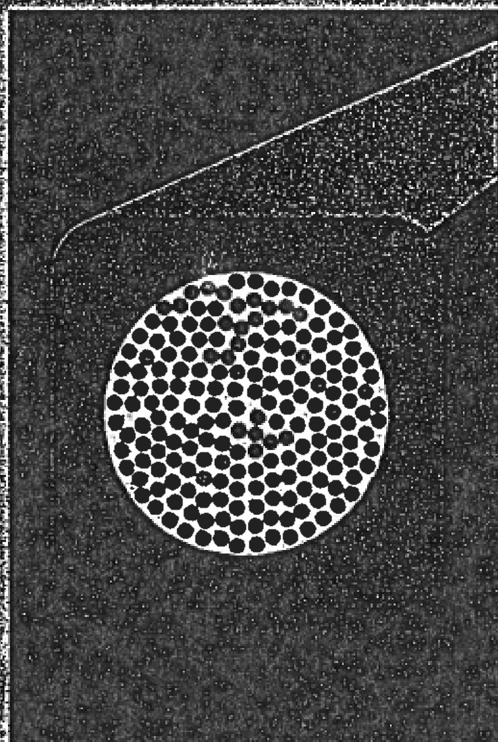
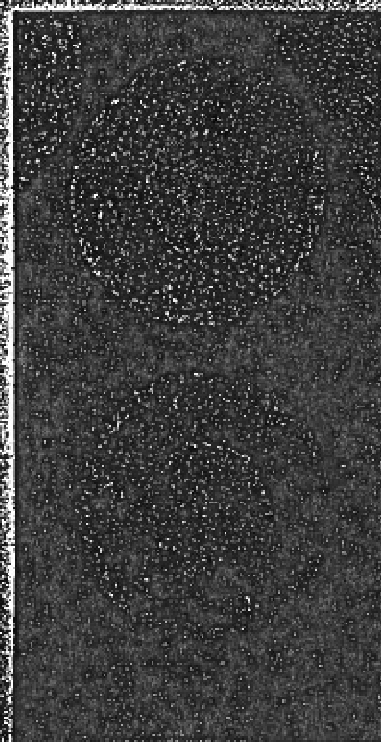
ALUMINIUM ALLOY JACKETED CABLE IN CONDUIT

Basic strand Cu/Nb-Ti	Ø = 0.55 mm	Void fraction	40%
Filaments	Ø = 27 μm	External jacket dimension	18.8 mm x 18.8 mm
Strand Cu/s.c. ratio	2 : 1	Internal jacket dimension	Ø = 10 mm
RRR	> 180	J_c(6.2T, 4.2K)	2150A/mm²
Number of s.c. strands	192	Jacket material	6061 Al alloy
Cabling sequence	3x4x4x4		







Europa Metalli-LMI has developed a prototype conductor for Wendelstein-Stellarator (Max-Planck Institut Für Plasmaphysik - Garching bei München-D) consisting in an aluminium-alloy jacketed Nb-Ti based CIC conductor, obtained by a coextrusion process. The major advantages of such a conductor are the following:

- Possibility of obtaining several hundred meters of continuous unit lengths without any welding operations.
- The CIC conductor may be easily wound in a complex magnet configuration when the jacket is in the "soft" temper (as-quenched alloy) and can achieve the design strength after winding, by properly "ageing" the cable in the range of 130° to 180°C, depending on the Al alloy composition.

Properties of co-extruded aluminium from the 6000 series

- relatively soft during the compound (three-dimensional) winding process
- subsequent hardening process to meet the mechanical strength requirements

Aluminium-Alloy 6060T6 - AlMgSi1

Elastic limit: $R_{p0.2}$ [MPa]

100	Extruded
↓	
< 120	Stabilised
↓	
Wind	
↓	
270	Hardening at RT
↓	
350	4K

(EMI-LMI)

Degradation Study of critical currents

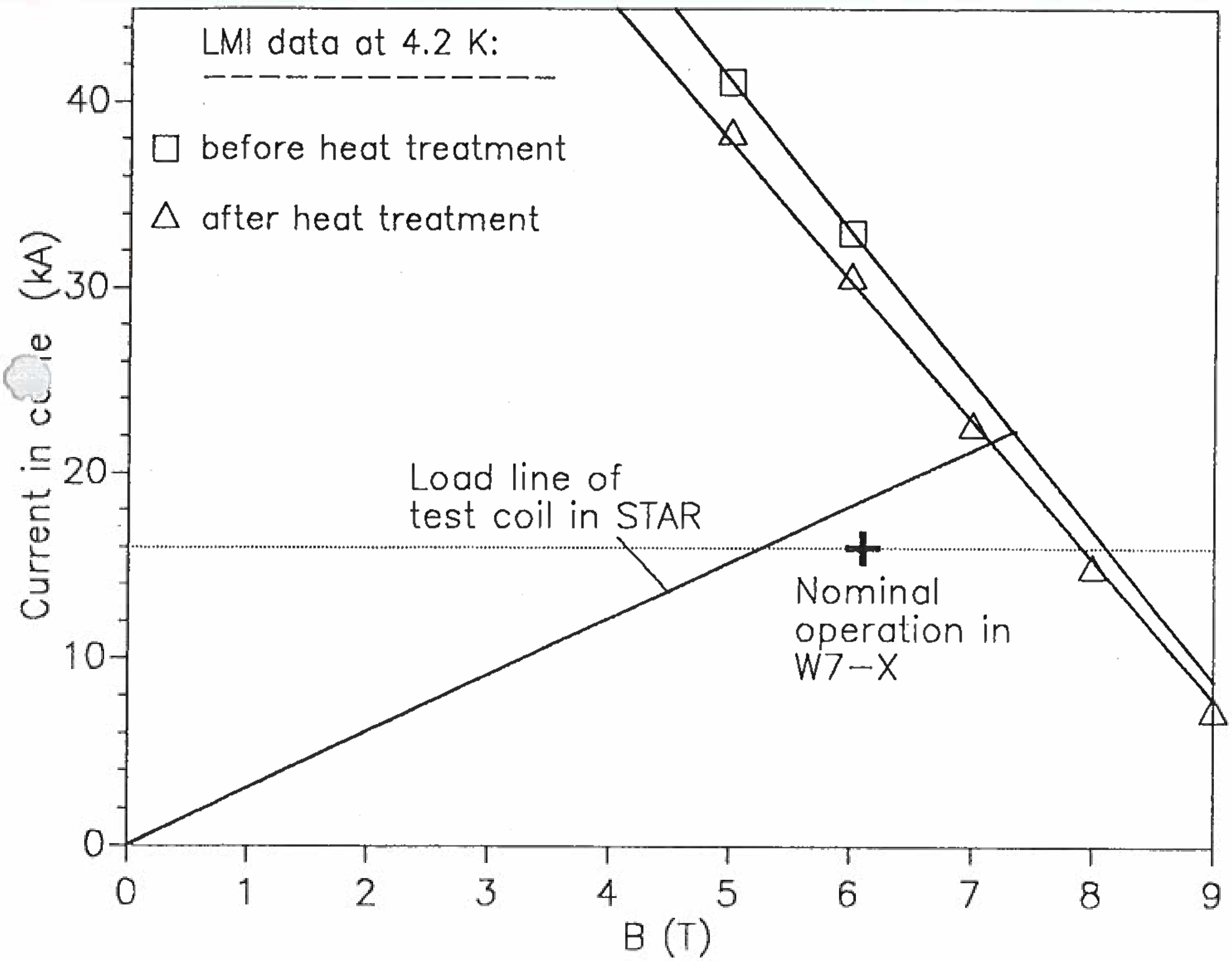
- The degradation of the strands after co-extrusion has been evaluated by measuring the critical current of short samples for different heat treatment temperatures resp. times

- The degradation of the cable after co-extrusion has been evaluated by measuring the critical current of short samples before fabrication and of triplets after co-extrusion of the cable

- The degradation at T=4.2 K and B=6 T was about 8 %

Degradation Study of critical currents (cont'd)

Commercial available strand 48 filaments 0.58 mm diameter Cu/Sc = 2.14 : 1 T = 4.2 K 0.1 μV/cm		
Time of heat treatment	30 s	120 s
Temperature (^{0}C)	%	%
0	100	100
400	85	79.6
500	74	45
550	32	13.5
600	4	-


LMI data at 4.2 K:
before heat treatment
after heat treatment
Load line of
test coil in STAR
Nominal
operation in
W7-X
Current in cable (kA)
B (T)
0
10
20
30
40
0
1
2
3
4
5
6
7
8
9

Pressure drop and heater experiments

- A 1.4 m long cable fabricated from copper strands have been installed in the HELITEX facility at KfK

- Pressure drop has been measured for various mass flow rates

- Evaluation of friction factor and comparison to parametrisations

1. Blasius equ.

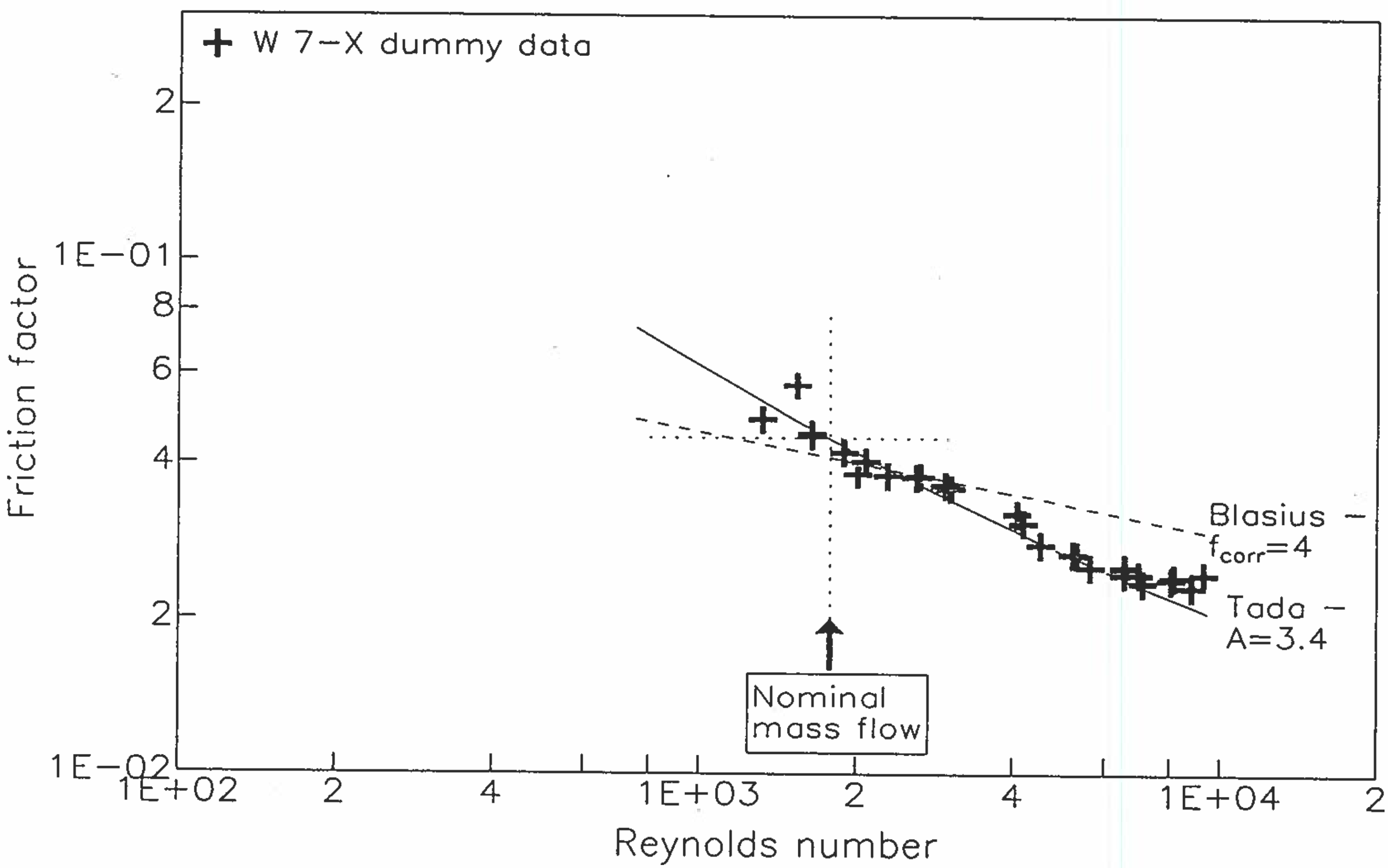
$$f = f_{corr} \cdot \frac{64}{Re}$$

2. Prandtl-Karman equ.

$$\frac{1}{\sqrt{f}} = 0.87 \ln(Re\sqrt{f}) - A$$

- Results:

1. $f_{corr} = 4$
2. $A = 3.4$



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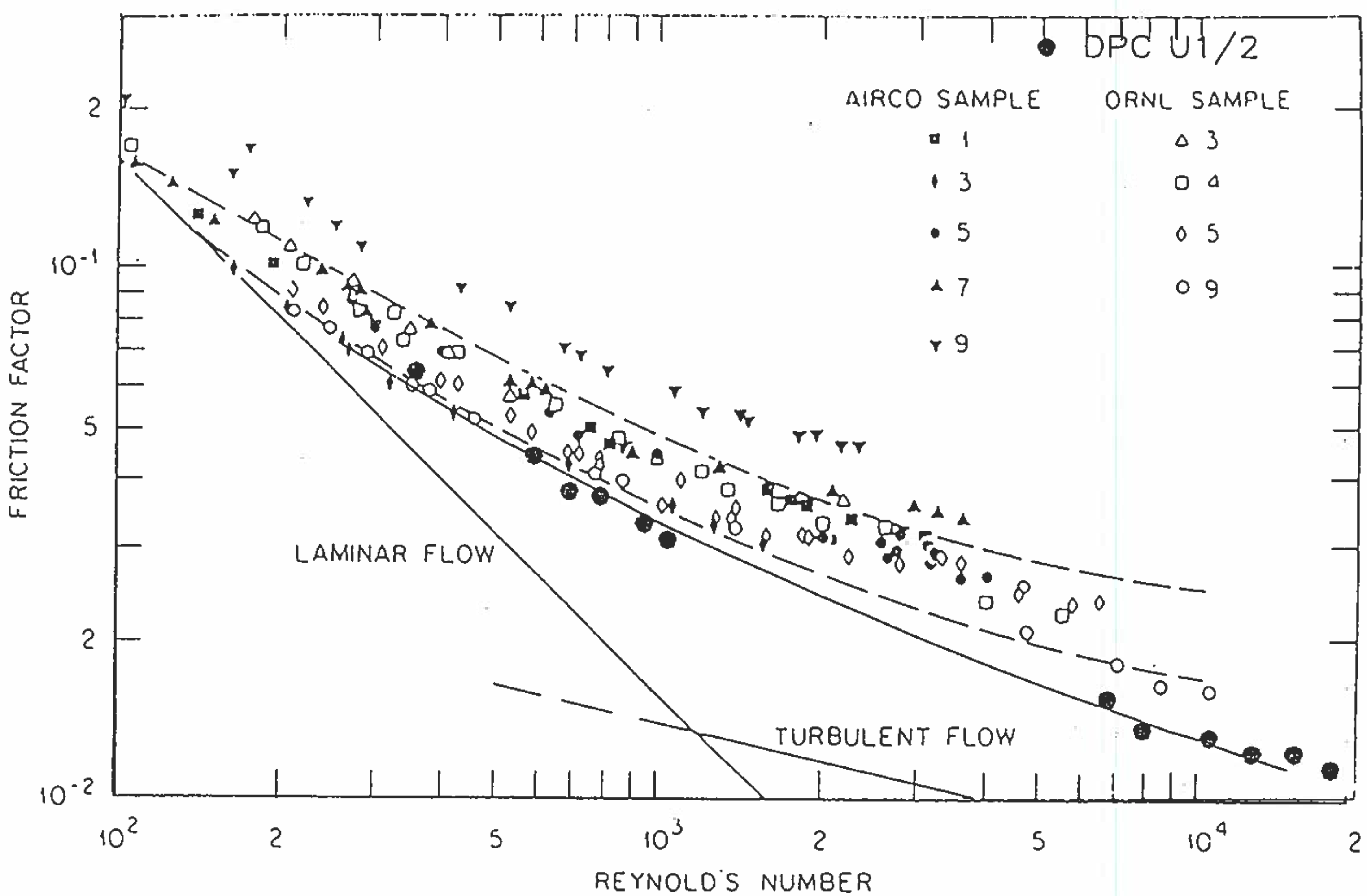


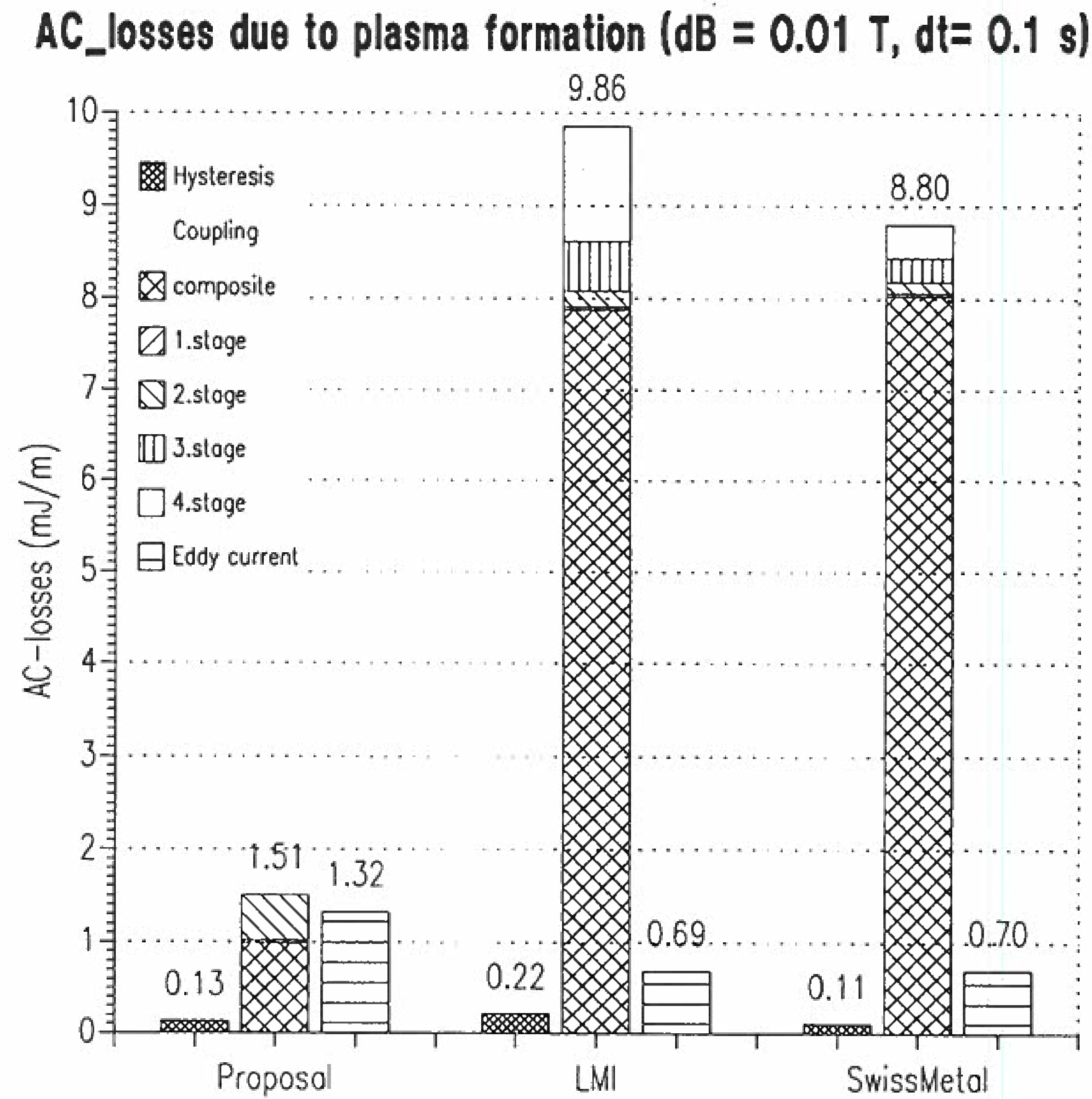
Pressure drop and heater experiments (cont'd)

- Conductor has been heated over a length of 20 cm and helium temperatures, heater temperature, pressure drop, and mass flow rates have been measured. Experiment has been done for various heating power resp. mass flow rates

- Evaluation of experimental data is under way

Stability, AC losses, and quench analysis

- Although stellarator uses a steady state magnetic field, AC losses occur
  - during plasma formation
  - during divertor sweeping if any
  - due to ripple of power supply
- Intensive investigations have been done by calculating the AC losses for the different field changes analytically
- Electromagnetic stability has been calculated without taking into account the aluminium jacket
- A detailed numerical quench analysis for the test coil has been done using the codes SARUMAN (L. Bottura, NET) and MAGS (R. Meyder, KfK)



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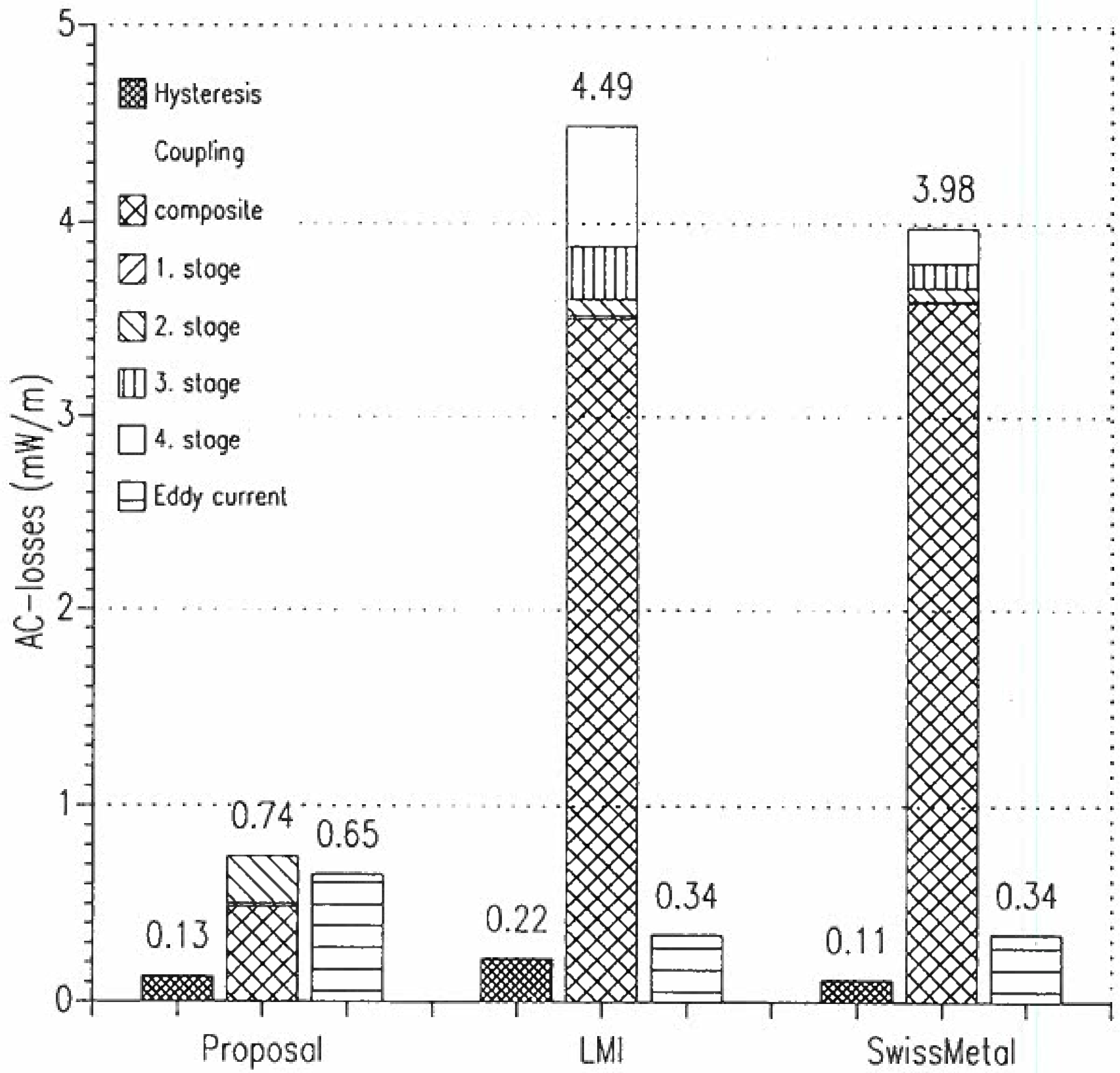
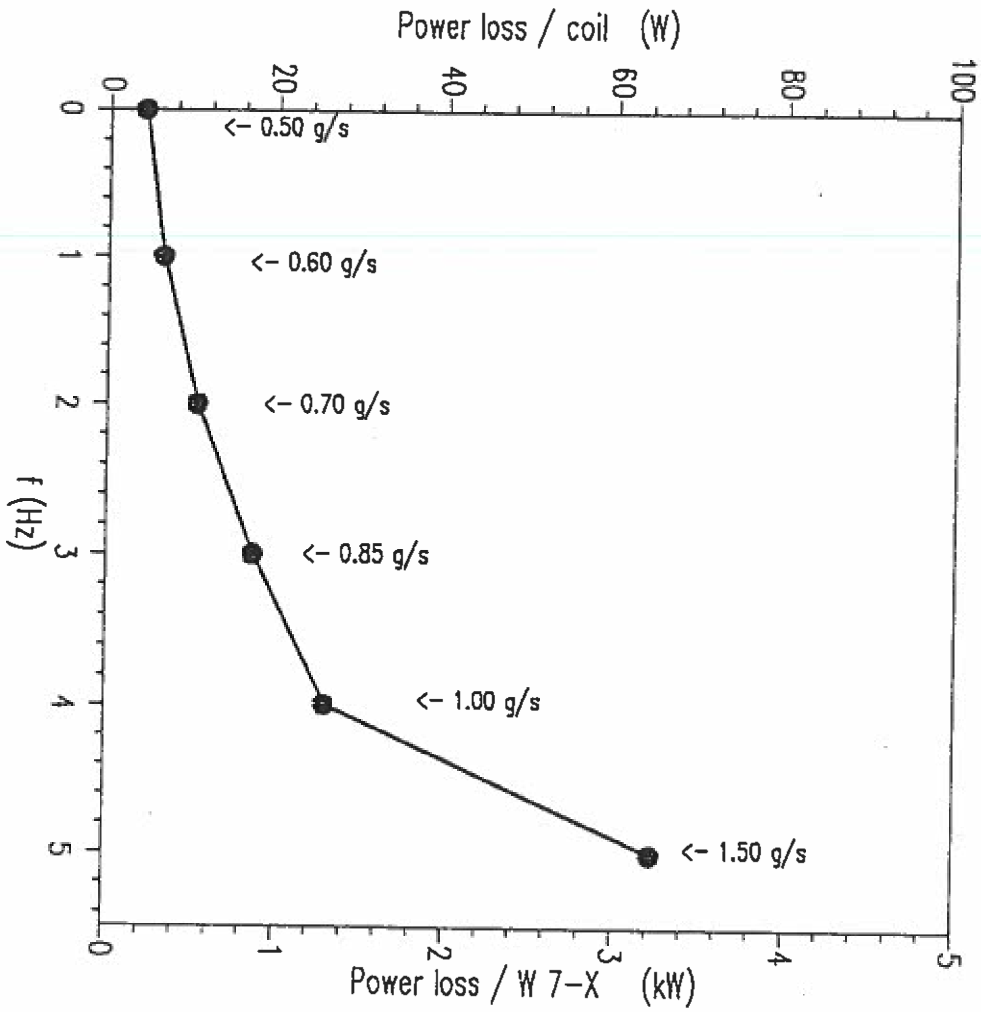
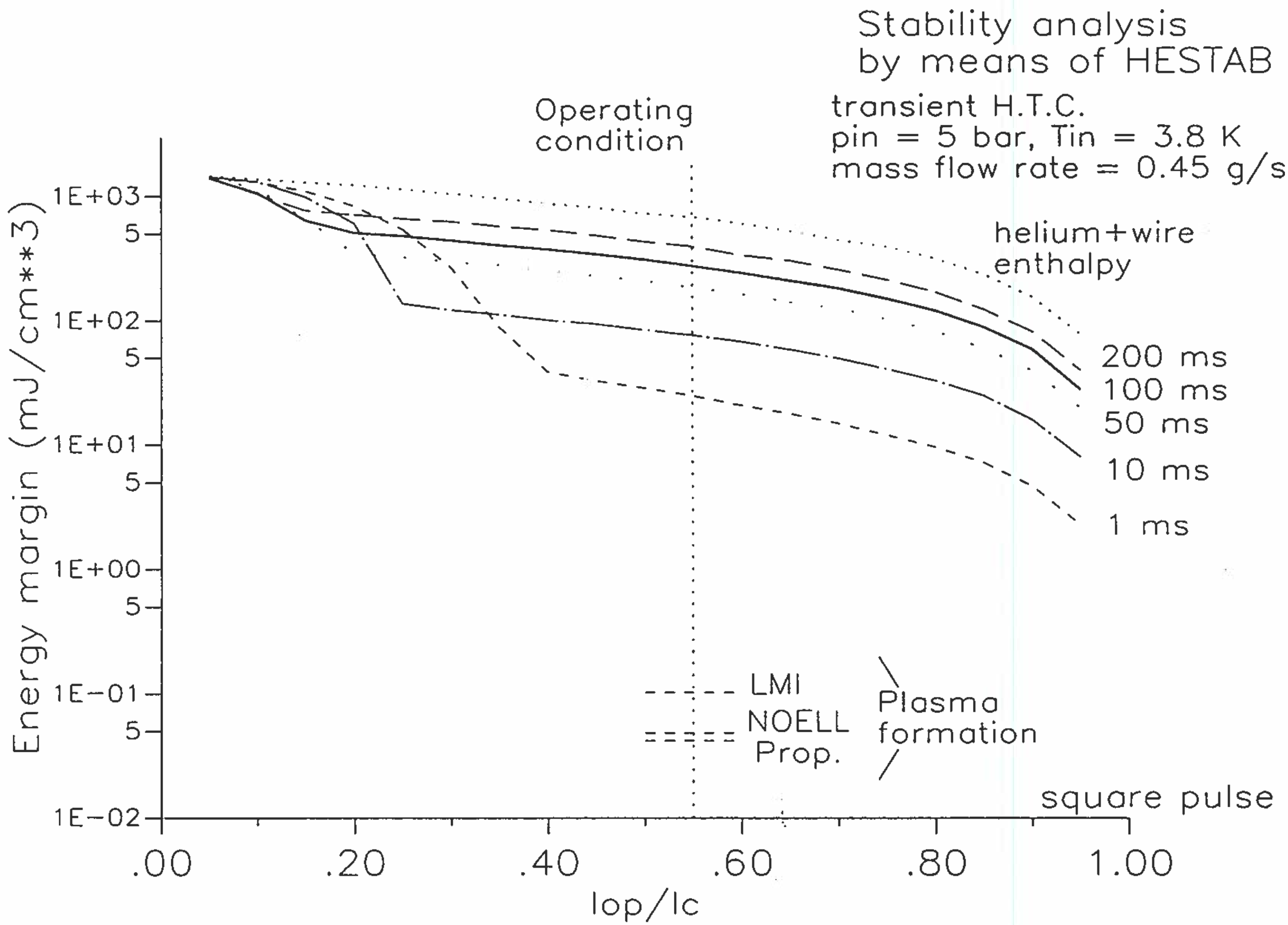
AC_losses due to divertor sweeping (dB = 50 Gauss, f = 1 Hz)





Power loss / coil (W)
f (Hz)
Power loss / W 7-X (kW)
<- 0.50 g/s
<- 0.60 g/s
<- 0.70 g/s
<- 0.85 g/s
<- 1.00 g/s
<- 1.50 g/s



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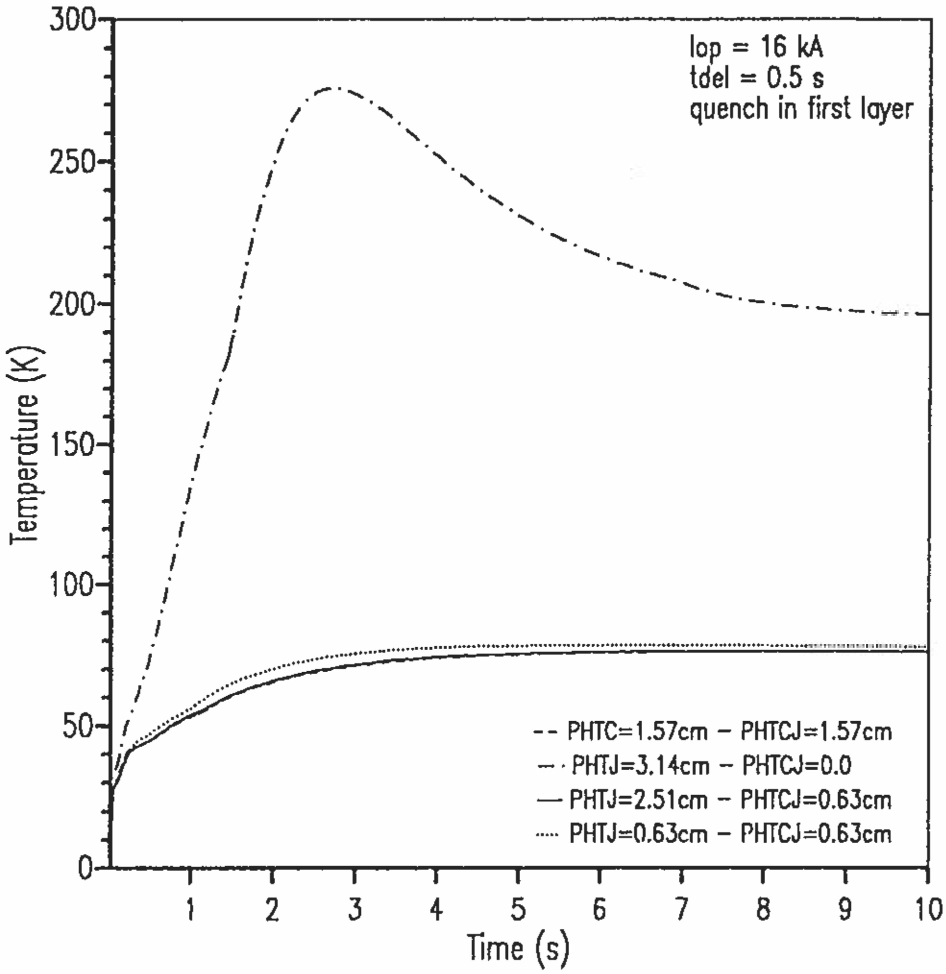

Iop = 16 kA
tdel = 0.5 s
quench in first layer
PHTC=1.57cm – PHTCJ=1.57cm
PHTJ=3.14cm – PHTCJ=0.0
PHTJ=2.51cm – PHTCJ=0.63cm
PHTJ=0.63cm – PHTCJ=0.63cm
Temperature (K)
Time (s)
0
50
100
150
200
250
300
1
2
3
4
5
6
7
8
9
10

Construction and test of a solenoidal model coil

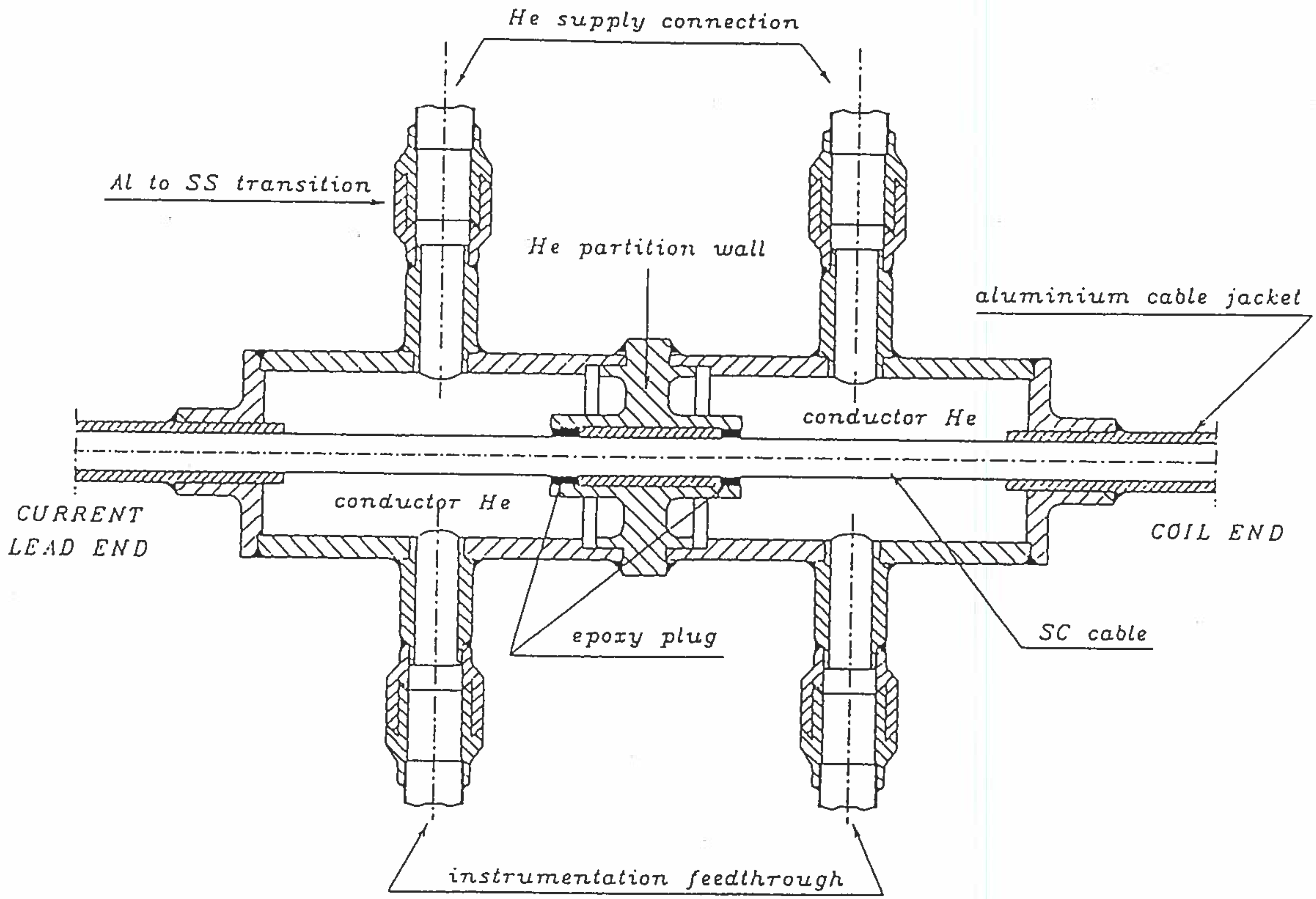
- Test goals:

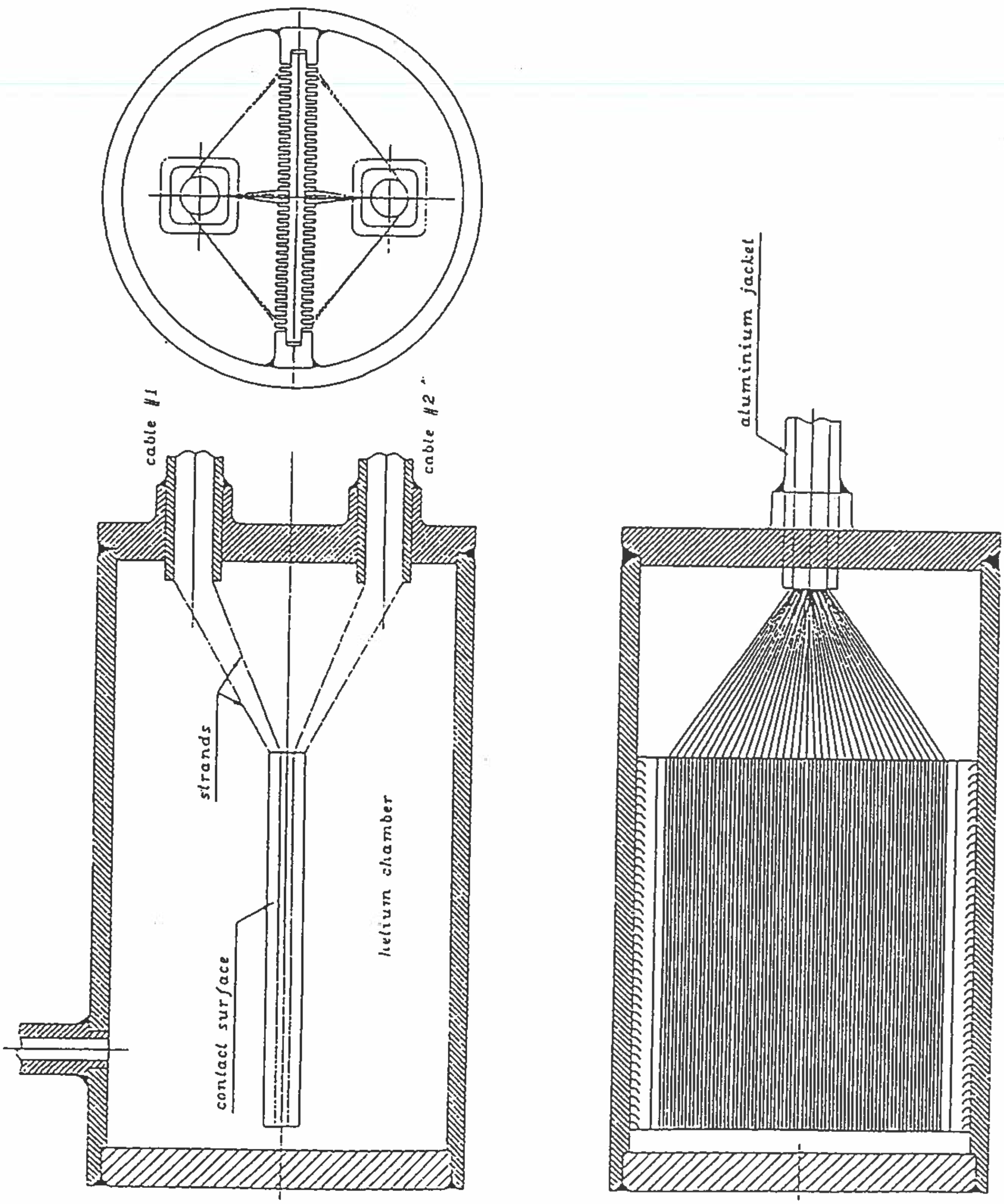
  Measurement of the $J_c(B)$ behaviour
  Thermal stability
  AC loss behaviour for a frequency of a few Hz
  Test of components and techniques

  He-inlet and -outlet
  Electrical joints between conductors
  Electrical demountable joints between cable and current lead

  Proof of welding technique

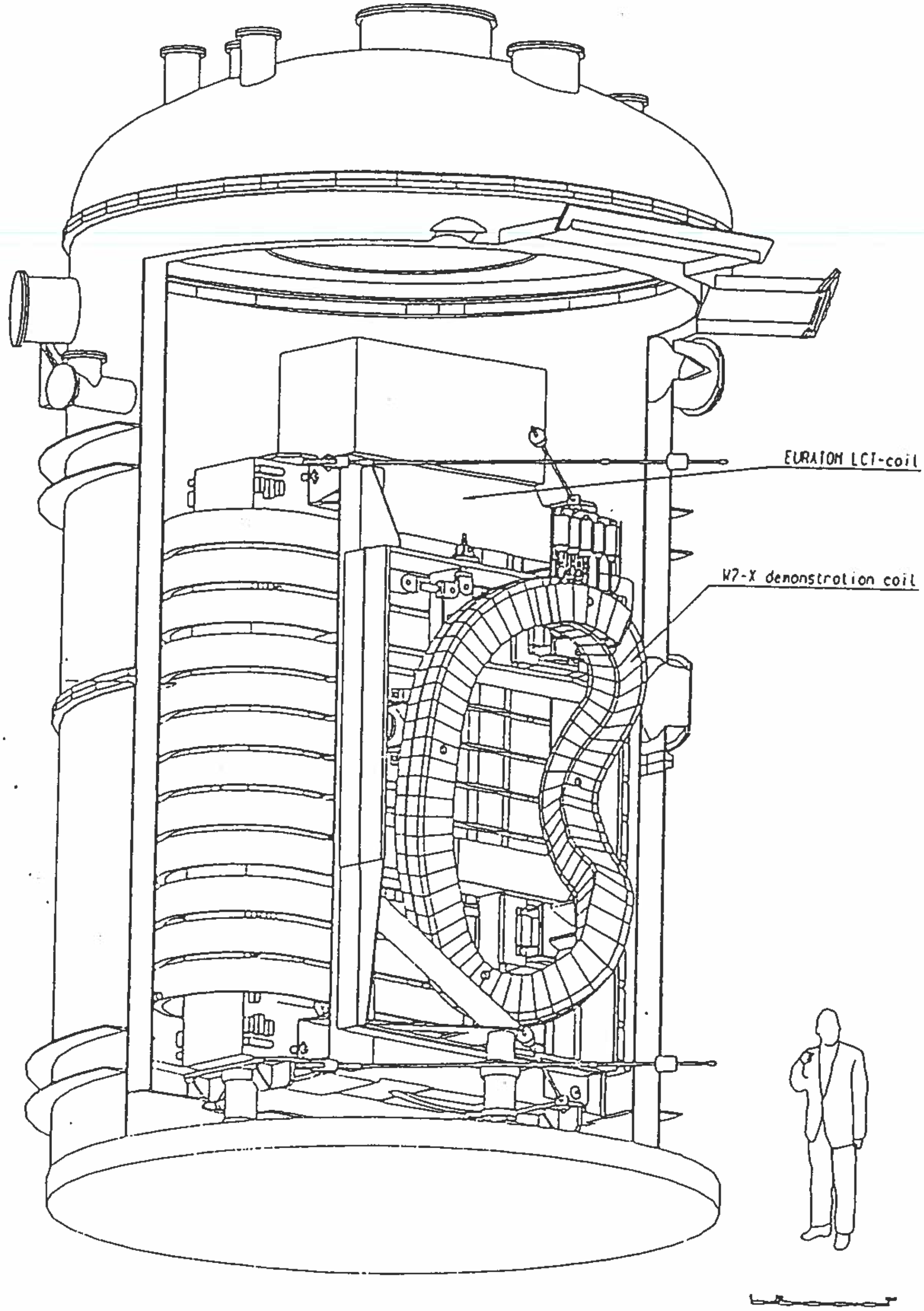
- For investigations of the quench behaviour of the W 7-X conductor, a small test coil will be constructed and tested in the STAR facility


He supply connection
Al to SS transition
He partition wall
aluminium cable jacket
conductor He
conductor He
CURRENT
LEAD END
COIL END
epoxy plug
SC cable
instrumentation feedthrough


cable #1
cable #2
strands
contact surface
helium chamber
aluminium jacket

Conclusions and outlook

- The development of a conductor especially appropriate for the winding process of modular non-planar coils is finished
- The second step - test of the conductor in a solenoidal model coil - is in progress
- The design of a 1:1 demonstration coil is finished
- The Technical Specifications are in the industry



TOSKA DEMONSTRATION COIL TEST FACILITY