THE TESLA REFRIGERATION SYSTEM

Status Report by Oct. 1993

by

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1. Introduction:

TESLA is a proposed superconducting electron linac of about 30 km length. Its active RF resonator cells are made of niobium which have to be cooled to a temperature of about 2 K in order to become superconducting. A large system for production and distribution of refrigeration power has to be provided. The present state of ideas for the realisation of this system are summarized.

2. Requirements:

In preceeding work shops [1]; [2] on the TESLA system some basic features have been decided:

2.1 Operating temperature: $T_{op} \approx 2$ K.

2.2 Cooling medium: liquid helium, boiling at equilibrium vapor pressure of: $P_{op} \approx 30$ mb.

2.3 Cooling mode: bath cooling

2.4 A largely wide spread system like TESLA cannot be supplied from one single refrigeration station like HERA. A subdivision into 16 subunits of 1880 m length, each supplied by its own refrigerator, was agreed. The refrigerators of two adjacent subunits are installed in common refrigerator buildings, so 8 cryogenic halls are required (Fig. 1).

Each single cavity (Fig. 2) is placed in a helium container (Fig. 3 + 4) , several cavities are assembled in a common cryostat called module (Fig. 5 + 6). The total subdivision of TESLA is listed in Tab. 1.

3. The System

3.1 Cooling capacities

Based on present cryostat designs estimations of static and dynamic (RF power) losses have been performed. The required cooling capacities are listed in Table 2. A safety factor of 1.5 has been included both for the refrigerators and flow areas in the distribution system in order to provide sufficient redundant capacity (Table 2).

3.2 Main features of the cryogenic subunit system.

The principal flow schema is displayed in Fig. 7; temperatures and pressures at the most important points are listed in Tab. 3.

3.2.1 The 2 K circuit

Monophasic helium (3 bar, 2.2 K) ist supplied at point 7, (Fig. 7). From the supply tube going through all modules a fraction of about 1/12 of the massflow is expanded through JT-valves into each string. Gas and liquid move through the upper space in the cavity containers (Fig. 3 + 4) with increasing vapor fraction due to evaporation by heat loads. Excess liquid at the end of each string is collected in an end box and completely evaporated by electrical heaters. In order to minimize the required heating power, the flow rate through the JT-valve is controlled by the level in the end boxes. In equilibrium the level has to remain constant and no heating is required.
The returning vapor (which is overheated to a small extent by the heat load of the 0.3 m diameter line) exchanges heat in HX 6 with the incoming 4.4 K flow for the 2.2 K supply. It leaves HX 6 at the warm end at a pressure of $p \approx 30$ mb and a temperature of $T \approx 3.4$ K. Here it is compressed to about 1.1 bar by means of 4 stages of cold compressors of the CEBAF type. The gas is then added at a higher temperature (due to compression work) to the return flow of the refrigerator.
There are different possibilities for the compression process indicated in Fig. 7:

a) straight forward compression without intercooling (CEBAF-process)
b) intercooling to 4.5 K after the second stage
c) intercooling at a higher temperature level

The final choice of the compressor circuit will be made later, considering more experience with the CEBAF system which at present is the only existing one of this size.

3.2.2 The 4.5 K circuit

Monophasic supercritical helium (5.4 bar > p > 3 bar; 4.4 K < T < 5.4 K) is supplied to the subunit at point 5. The supply flow is first fed in series through all quadrupoles of the unit in order to provide the lowest possible operating temperature for these magnets. The return flow is cooling the 4.5 K shields of the modules, all in series as well.
At point 11 (Fig. 7) a fraction of the flow is expanded into the 4.3 K bath cooler HX 5 in order to supply the liquid for precooling. The remainder is recooled to the bath temperature. After having passed the 2.2 K heat exchanger HX 6 it enters the subunit (see 3.2.1).

3.2.3 The 40/80 K circuit

Cold helium gas ($T = 40$ K; $p = 17$ bar) is supplied at point 2 for cooling of the 60 K (average value) radiation shields of the modules.
In parallel a second flow enters at point 3 in order to cool the HOM-absorbers in the quadrupoles. Both streams return through a common line at point 1 ($T \approx 80$ K, $p \approx 16$ bar).

3.2.4 Cold boxes with heat exchangers, turbines and cold compressors as well as warm compressors, auxiliary equipment and storage capacities (warm or/and cold) will be installed in or around the cryo halls (details have not yet been worked on).

3.2.5 Connecting valves between adjacent subunits will be provided for redundant operation modes (running 2 subunits with only 1 refrigerator in case of non HF powered standby).

3.2.6 Additional liquid nitrogene heat exchangers should be supplied in the cold boxes for fast cool down from room temperature to 80 K and for the liquefaction phase (filling the cryostats).

3.2.7 Gas flow rates
The maxium gas flow rates per subunit are listed in Tab. 4.

3.2.8 Electrical power
The electrical power input, required at full refrigeration power is listed separately for 2 K, 4.5 K and 40/80 K cooling in Tab. 5.

3.2.9 Helium inventory
Table 6 gives a summary of helium inventory, Tab. 7 presents the required storage capacities, alternatively for liquid or gas storage.

4. Performance investigations

Using the present knowledge of cryostat design and heat loads, some first computer simulations have been executed. They give pressures and temperatures in the cavity cryostats, depending on their geographical location in respect to the refrigerators. Independant calculations [3); 4)] give results in sufficiently good agreement. Some examples are given in Fig. 8 to 15.

5. Cost Estimates

At present no consultations of industry have been made. A rough estimate of costs is included below:

Basis of estimate:

1 HERA (6700 $W_{4.5K}$/20 000 $W_{40/80K}$ / 20 g/s) Refrigerator

Price 1985	**DM 12.0 x 10^6**
Price extrapolated to 1993 (Inflation 5% /anno)	**DM 17.7 x 10^6**

Assumption:

Price ~ $(\text{power})^{0.7}$
at comparable efficiencies the electrical input power represents the overall refrigeration power, then

$\text{Price}_{\text{Tesla}} = \text{price}_{\text{Hera}} \times (5.6 \times 10^6 / 2.7 \times 10^6)^{0.7}$

The price for one Tesla refrigerator, including:

4.5 K -Cold box with heat exchangers + turbines
warm compressors
purification
internal tubing and valving
instrumentation
cold compressors **(about 2×10^6 DM)**
2 K heat exchangers

amounts to :

29.5×10^6 DM **per unit**

472×10^6 DM **for 16 units as required**

This number does not include:
gas storage (warm or cold tanks)
recovery devices (high pressure compressors)
controls (process computers)
warm and cold auxiliary tubing and valves in the tunnel
and many other hidden items to be discovered in the detailed design studies.

An addition of about 100 to 200 x 10^6 DM may increase the final refrigeration investment costs to about

~ 600×10^6 DM

6. Summary, comments and open problems

The list below has to be considered as non complete, not very systematic!

1. Safety valves (from helium vessel to 300 mm tube).
   We would like to have only one per 150 m cryogenic/vacuum unit, at the feed end (vent at other end does exist anyway). But this might mean:
   a. Assuming a venting rate is limited by a reasonably small air hole size.
   b. Higher allowable COLD pressure, certainly exceeding the 2 bar range.
   c. Larger interconnecting tubes.

2. Calculate trade-offs for the relief only at the feed end - air hole size allowable overpressure, etc.

3. Investigate possible designs for limiting the maximum air penetration into the beam vacuum region. Can the length of a vented zone be limited by fast acting vacuum valves between strings?

4. Investigate the behaviour of a total subunit after discharge of 1 or several strings into the 300 mm return line (can (3 + x) bar in the cavity cryostats be maintained without or with acceptable He losses?)
5. The 148 m cryogenic unit of 12 modules would also be a good size for an insulating vacuum unit. There should be insulating vacuum breaks every 148 m.

6. Need to study inventory handling and warmup methods.

7. Helium storage must be mostly as liquid. (SSC has 90% liquid, 10% warm gas storage). A nice method for emptying the helium vessels around the cavaties is to take the saturated 4.3 K vapor boiloff into the refrigerator and send the liquid helium produced by the refrigerator into a big storage dewar.
(A static heat load of 5 W per module and 449 liters of liquid per module requires 2.8 days to boil liquid out.).

8.Cryostat designers should try to reduce the liquid volumes of the cryostats!

9. What are the tolerable circumferential temperature gradients on a cavity during cooldown and warmup ?

10. If a higher maximum operation temperature of quadrupoles can be tolerated (4.7 - 4.75 K) it is recommended to keep the 2.2 K supply flow entirely separated from the 4.5 K shield flow.

11. If the flow area in the HOM absorbers in the quadrupoles could be enlarged, the separate 40/80 K forward line could be eliminated.

10. CEBAF experience is important in general, but in particular with respect to cold compressors and how they are incorporated into the system.

13. TESLA following the curvature of the earth gives less problems compared with a planar linac.

Appendix:

Approaches to Minimum Cryostat Design

One of the disadvantages of the present TESLA cryostat design is the large dead volume around the RF-resonators (Figs. 3 + 4). This volume has to be filled with liquid helium with the consequence that the amount of helium to be provided is unnecessarily high (Tab. 5). The large volume is a consequence of the fact that the vapor has to pass all cryostats of one string through the upper part of the helium containers with increasing flowrate from the inlet end to the outlet. The vapor flow area has to be large enough in order to keep the pressure variations (and consequently the temperature variations) sufficiently low.
A much smaller cryostat design would be possible if the vapor is returning not through the cryostats but through an extra tube outside the liquid containers.
In this case the helium container can surround the resonator cells in a very short distance (Fig. 16), thus reducing the liquid volume to a minimum. There are different proposals to operate such cryostats in the system:

1.1 Direct venting into the 300 mm return tube[4).

One solution is to connect the cryostats to the 300 mm vapor return tube. In order to avoid liquid flow in the 300 mm tube the cryostats have to be through connected by longitudinal tubes near the bottom. The diameter of these tubes is only about half the size (~ 50 mm) of the vapor tubes in the present design.
Figs. 16 + 17 demonstrate the cryostat design schematically. The reduction of volume and helium inventory is presented in Tab. 8.

1.2.1 Steady state operation

A steady state flow diagram is given in Fig. 18. A liquid flow from one cryostat to the next is maintained both by the pressure gradient in the vapor tube and by level difference between adjacent cryostats (Fig. 19).
Figs. 20 to 23 demonstrate the variation of pressures, temperatures and liquid levels along a Tesla subunit.

1.2.2 Cool down/Warm up

Cool down and warm up of the system cannot be performed in longitudinal direction. Any gas flow would escape into the return line within the first few cavities. Therefore a parallel cooling according to Fig. 24 is proposed. The cooling (or warm up) gas is distributed through a parallel tube and fed individually into the cavities through small diameter connection tubes. If the flow resistance of the connecting tubes is large compared to the resistance along the distribution line, all cryostats receive cooling flows uniform within about ± 5%. Fig. 25 represents the cool down behaviour of one cryostat which is identical for all cells of one subunit.
If necessary, the cooling speed from room temperature to ~ 80 K can be increased by concentrating the cooling capacity of one refrigerator on sections of 3 or 4 strings. When the first group is cold the next group will be cooled with the same speed. Since the cooling gas passes the 4.5 K shields of all cryostats of the unit before entering the cavities, a group once being cold cannot drift to higher temperatures during the cooldown of the next ones.

1.2 The parallel 100 mm vapor tube[5].

An other possible solution is to use a 100 mm diameter tube parallel to the cryostats (Fig. 26). In the tube both liquid and vapor flow from inlet to outlet. Each cryostat is connected at both ends to the tube. In order to insure a flow through the cryostats a nozzle in the tube at the down stream end provides a pressure drop which is not only necessary for steady state operation but also for cool down and warm up.

1.2.3 Other solutions

There are some other solutions (Fig. 27 for example)[6] in discussion. They will have to be worked out more in detail.

SUMMARY

1. By evacuating of the He vapor and of the TESLA cavitiy containers directly into the 300 mm return pipe, the He inventory of TESLA can be reduced by an amount of

87438 kg $\rightarrow$ 5 x 10^6 DM.

2. Storage capacities can be reduced by about 50%.

3. It is demonstrated by computer-simulation that a steady state operation is possible with He level variations within ± 2,5 cm which is tolerated.

4. Cool down and warm up must be performed for all cryostats in parallel. With reasonable flow rates one subunit can be cooled from 300 K to 80 K within 12 h or even faster with very low temperature gradients.

5. In case of accidential vacuum break down in the beam room the evaporated helium can be vented into the 300 mm return pipe with negligible low pressure drop. By this way

the pressure safety problem
is shifted from the cavities
to the beam returnline.

First estimates result in 3 or 4 safety valves per 1880 m subunit, venting the return line into the atmosphere in order to keep the pressure sufficiently low (Cold gas storage volumes should be considered in order to avoid He-losses in case of these events).

6. It seems that any of the new designs is superior to the old one.

The cryostat design for
TESLA 500 (1 + x)
should be changed!

References:

1. D. Proch, C.H. Rode, Summary of Cryogenic Group Discussions, Proc. 5th Workshop on RF Superconductivity, August 19 - 23, 1991, Vol. 2, p. 1049. DESY M-92-01, April 1992

2. G. Horlitz, T. Peterson, Summary of Cryogenic Group Discussions, TESLA Collaboration Meeting and Design Workshop March 10 - 12, 1993, Fermilab, Batavia, Illinois, DESY Print TESLA 93-18, May 1993

3. T. Peterson, private communication

4. G. Horlitz, TESLA Refrigeration with Minimum Volume Cryostats, TESLA Collaboration Report, to be published

5. T. Peterson, A Reduced Inventory Helium Vessel for TESLA, TESLA Collaboration Report, to be published

6. T. Peterson, D. Trines, private communication

Table 1:

Actual subdivisions of Tesla:

Module consisting of:

8 cavity cells operating at $T = 2$ K

1 quadrupole + beam position sensor + current leads operating at $T = 4.5$ K

1 HOM - absorbtion section in the quadrupoles, operating at $40 \text{ K} < T < 80$ K

4.5 K thermal shield, operating at 4.5 K

60 K thermal shield, operating at $40 < T < 80$ K

Length of one module: $L_{mod} = 12.2$ m.

String consisting of:

12 modules

1 inlet can with JT-valve and phase separator — **loop control via liquid level in the last module and JT-valve**

1 end can with liquid level indicator

Length of one string:

$L_{str} = 12 \times L_{mod} + 1.6 \text{ m} \rightarrow L_{st} = 148$ m

Subunit consisting of:

12 strings

1 refrigerator

Length of one subunit:

$L_{su} = 12 \times L_{str} + 104 \text{ m} = 1880$ m

Half linac (250 GeV) consisting of:

8 subunits

4 refrigerator halls with refrigeration equipment for 2 subunits per hall

Length of one half linac:

$L_{hl} = 8 \times L_{su} = 15040$ m

Total TESLA

There are 8 cryogenic halls, each hall housing two refrigerators including cold boxes, warm and cold compressors, purification system and warm (open air positioned) and cold gas storage tanks for the supply of two adjacent subunits.
Length of TESLA: $L_T = 2 \times L_{hl} + 1800$ m intersection area = 31880 m.

Table 2:

Calculated (c) and Design (d) Values for TESLA Refrigeration Capacities

Temperature		2	4.5	40/80	K
Module	c	21.0	19.4	100	Watt
	d	31.5	29.2	152.8	
String	c	278	232.8	1200	Watt
**	d	400	350	1833	
Subunit	c	3330	2793	14400	Watt
* **	d	5000	4200	22000	
Total	c	53300	44697	230000	Watt
**	d	80000	67046	352000	

*** Layout data for refrigerators**

**** Losses of all tubing (supply + return) are now included including summary of losses of all modules and all tubing (supply + return) in addition**

$q_{design} \approx 1.5 \times q_{calculated}$

Tab. 3: Temperatures and Pressures

Point *	Pressure [bar]	Temperature [K]
1	16.0	80
2	17.0	40
3	17.0	40
4	3.0	5.4
5	5.4	4.4
6	0.033	0.213
7	3.0	2.2
8	0.035	2.039
9	0.0375	2.65
10	≈ 4.2	4.55

*** Point numbers as indicated in Fig. 7**

Table 4: Maximum Gas Flow Rates in the Subunits
(c calculated d design)

T	2	4.5	40/80	K
c	169	180	69.5	g/s
d	242	270	104.3	g/s

Table 5: Primary Electrical Power Input

	$W_{2K} = 800 \times q_2$	$W_{4.5K} = 250 \times q_{4.5K}$	$W_{40/80K} = 25 \times q_{40/80K}$	ΣW	
Subunit	4.0	1.05	0.55	5.6	MW
Total	64.0	16.8	8.8	89.6	MW

Tab. 6: Helium Volumes and Masses in the TESLA Components

location	state	temperature [K]	pressure [bar]	density [kg/m³]	volume [m³]	mass [kg]
1 cavity	liquid He II	2.0	0.033	145.7	0.056	8.17
	vapor saturated	2.0	0.033	0.830	0.028	0.23
1 module	liquid He II	2.0	0.033	145.7	0.449	65.39
	vapor saturated	2.0	0.033	0.830	0.230	0.191
1 string	liquidHe II	2.0	0.033	145.7	5.386	784.68
1 string	vapor saturated	2.0	0.033	0.830	2.755	2.29
148 m return line	vapor (overheated)	2.05	0.033	0.816	9.776	7.977
148 m 2.2 K supply	supercritical	2.5	2.90	150.4	0.159	23.914
148 m 4.5 K supply + return	supercritical	4.5	3.00	129.6	0.729	94.478
148 m 70 K supply + return	gas	70.0	15.00	10.02	0.729	4.299

Σ = 918 kg per string / 11014 kg per subunit / 176218 kg total

Tab. 7 Storage volumes required

storage as	liquid (4.5 K)	gas (300 K, 20 bar)	
per subunit	91.8 l	3463	m^3
total TESLA	1470 l	55400	m^3

HERA (to compare with) has storage capacities of

2 x 10 m^3 liquid (4.5 K)

and 18 x 265 = 4770 m^3 warm gas (20 bar)

Tab. 8: Helium Volumes and Masses in the TESLA Components

Comparison between present and minimum volume cryostats

location	state	temperature [K]	pressure [bar]	density [kg/m³]	volume [m³]		mass [kg]	
					old	new	old	new
96 cavities (useful)	liquid He II	2.0	0.033	145.7	1.083	1.083	157.79	157.79
96 cavities (dead)	liquid He II	2.0	0.033	145.7	4.304	1.008	627.09	146.87
96 cavities (vapor space)	vapor saturated	2.0	0.033	0.830	2.755	0.027	2.29	0.22
148 m return line	vapor (overheated)	2.05	0.033	0.816	9.776		7.977	
148 m 2.2 K supply	supercritical	2.5	2.90	150.4	0.159		23.914	
148 m 4.5 K supply + return	supercritical	4.5	3.00	129.6	0.729		94.478	
148 m 70 K supply + return	gas	70.0	15.00	10.02	0.729		4.299	
148 m cool gas distribution	liquid He II	2.0	0.033	145.7	old 0.00	new 0.186	old 0.0	new 27.1

old Σ = 918 kg per string / 11014 kg per subunit / 176218 kg total

new Σ = 462 kg per string / 5549 kg per subunit / 88780 kg total

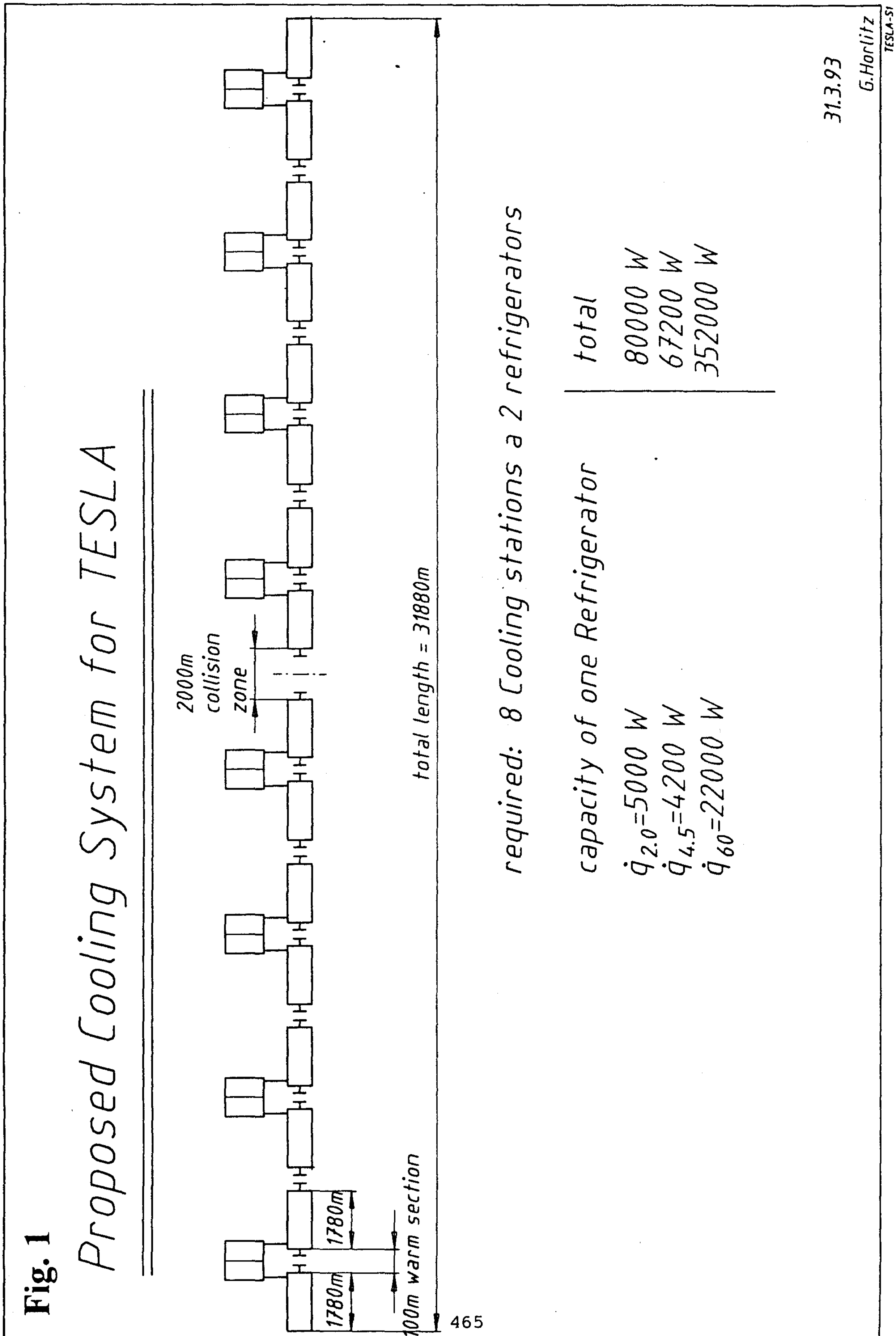
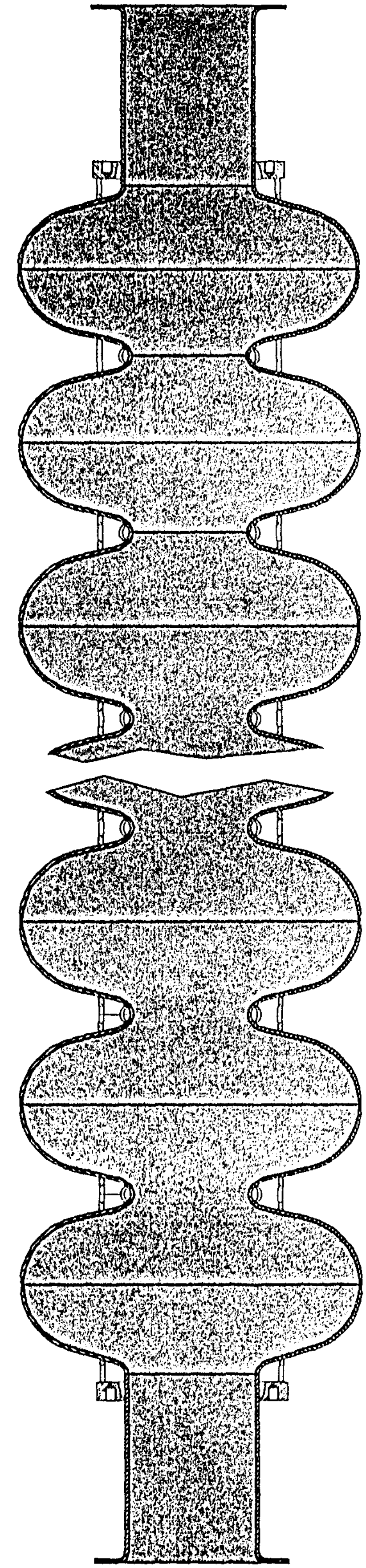

Proposed Cooling System for TESLA
2000m collision zone
1780m
1780m
100m warm section
total length = 31880m
465
required: 8 Cooling stations a 2 refrigerators
capacity of one Refrigerator
$\dot{q}_{2.0}$=5000 W
$\dot{q}_{4.5}$=4200 W
$\dot{q}_{60}$=22000 W
total
80000 W
67200 W
352000 W
31.3.93
G.Horlitz
TESLA-S1

Fig. 1



TESLA - CAVITY

Fig. 2

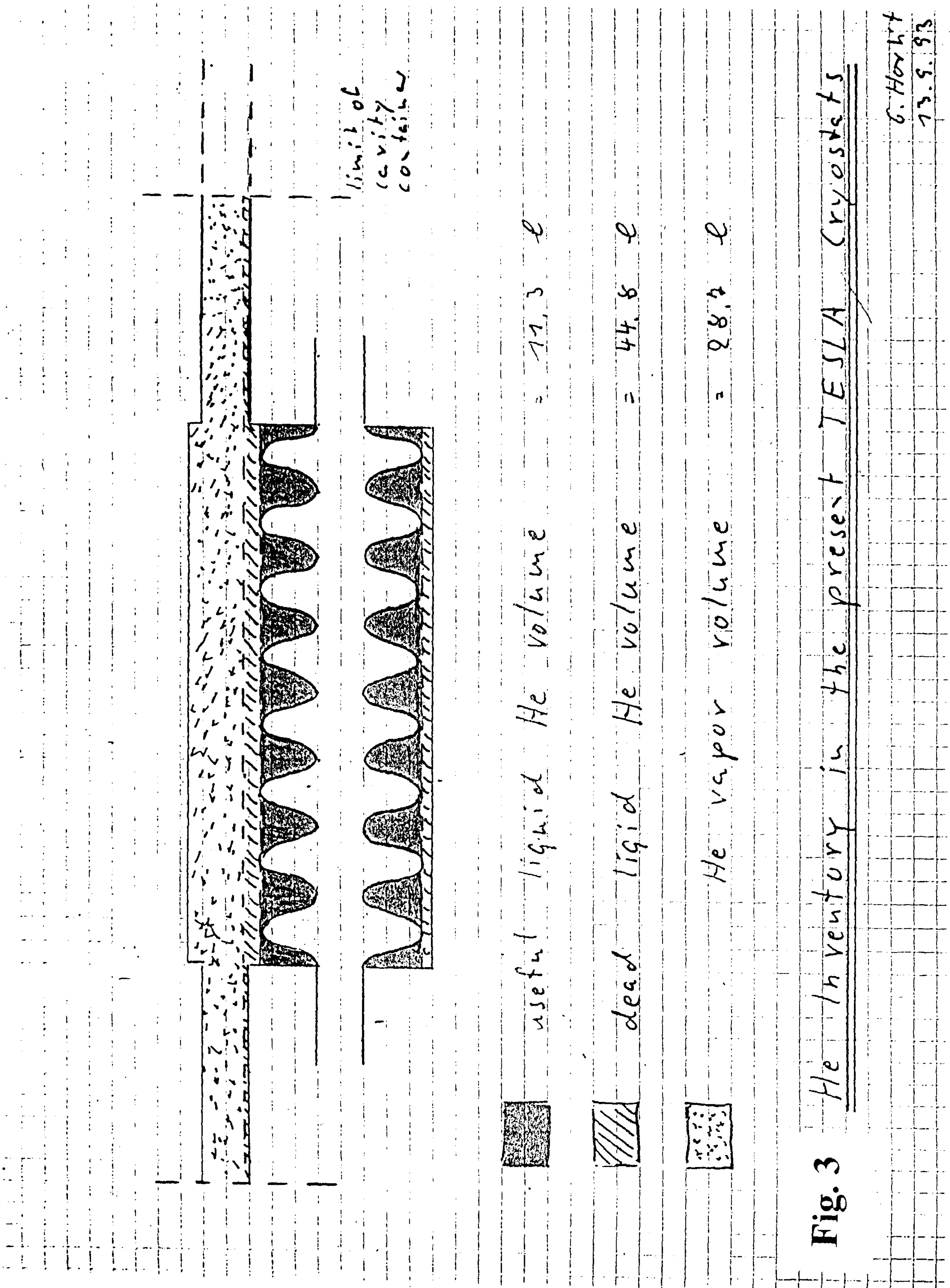
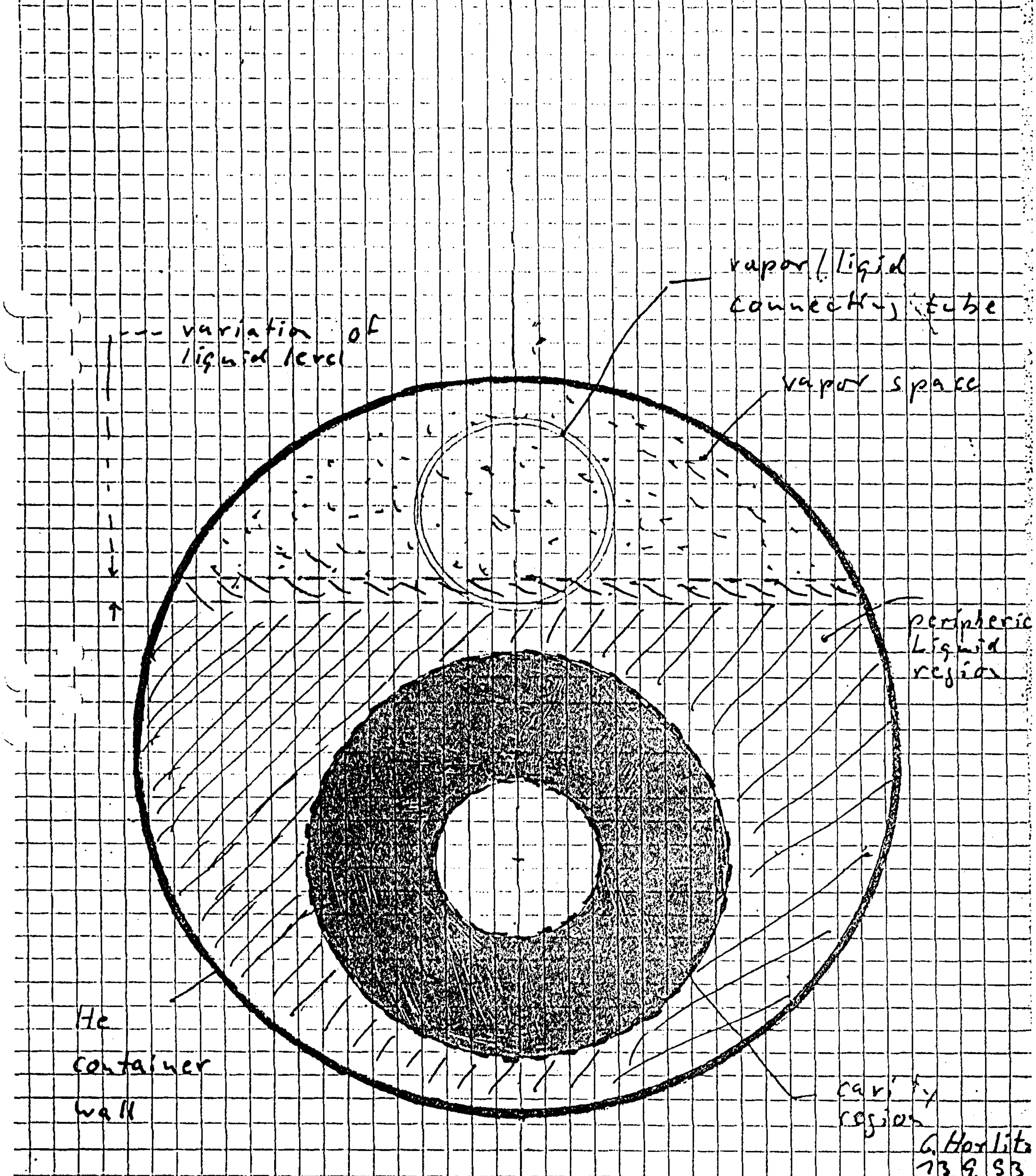

limit of cavity container
useful liquid He volume = 11.3 ℓ
dead liqid He volume = 44.8 ℓ
He vapor volume = 28.7 ℓ
He Inventory in the present TESLA Cryostats

Fig. 3

Fig. 4 He Container of present TESLA Cryostat (cross section)



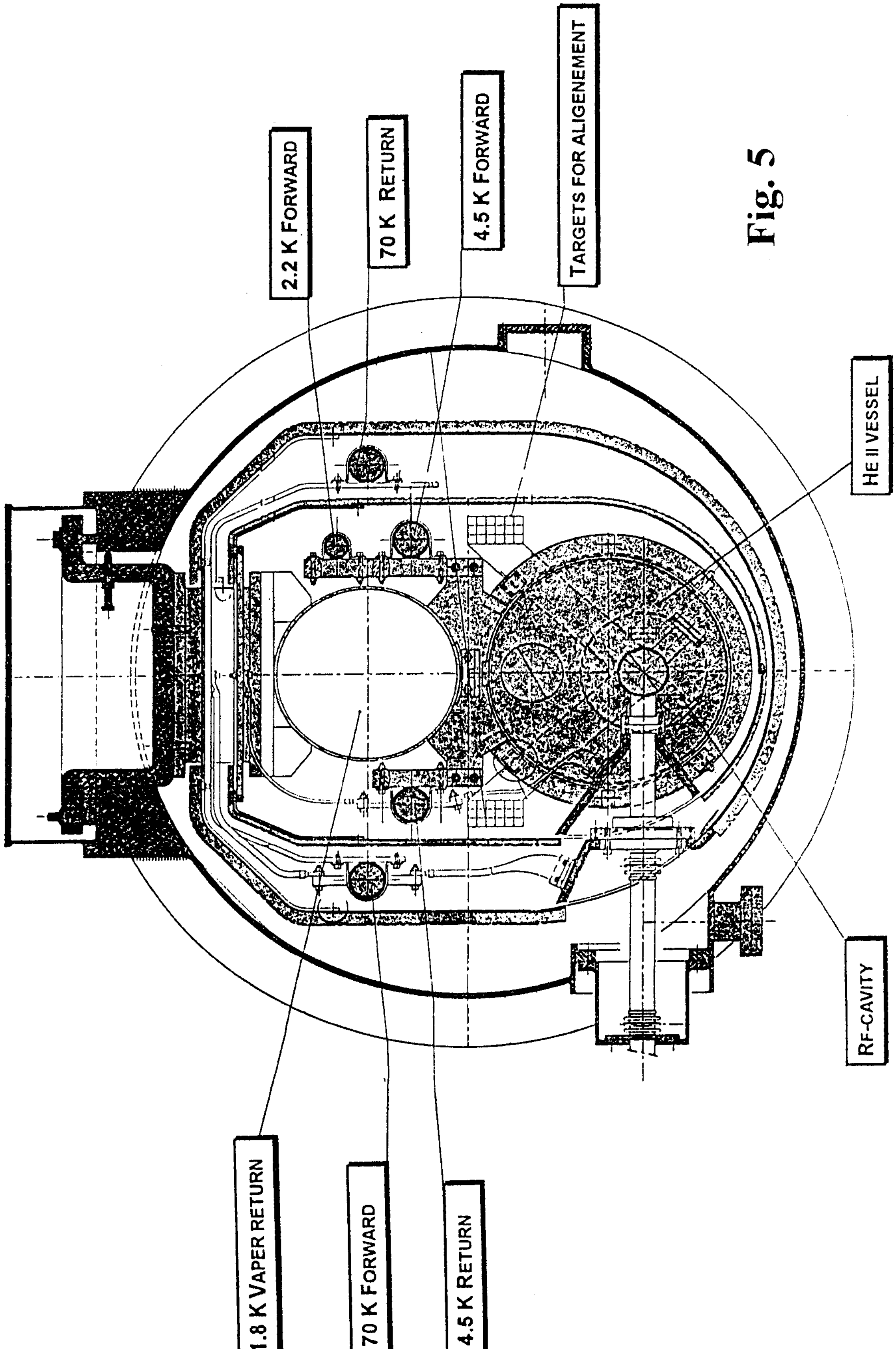

2.2 K FORWARD
70 K RETURN
4.5 K FORWARD
TARGETS FOR ALIGENEMENT
HE II VESSEL
RF-CAVITY
1.8 K VAPER RETURN
70 K FORWARD
4.5 K RETURN

Fig. 5

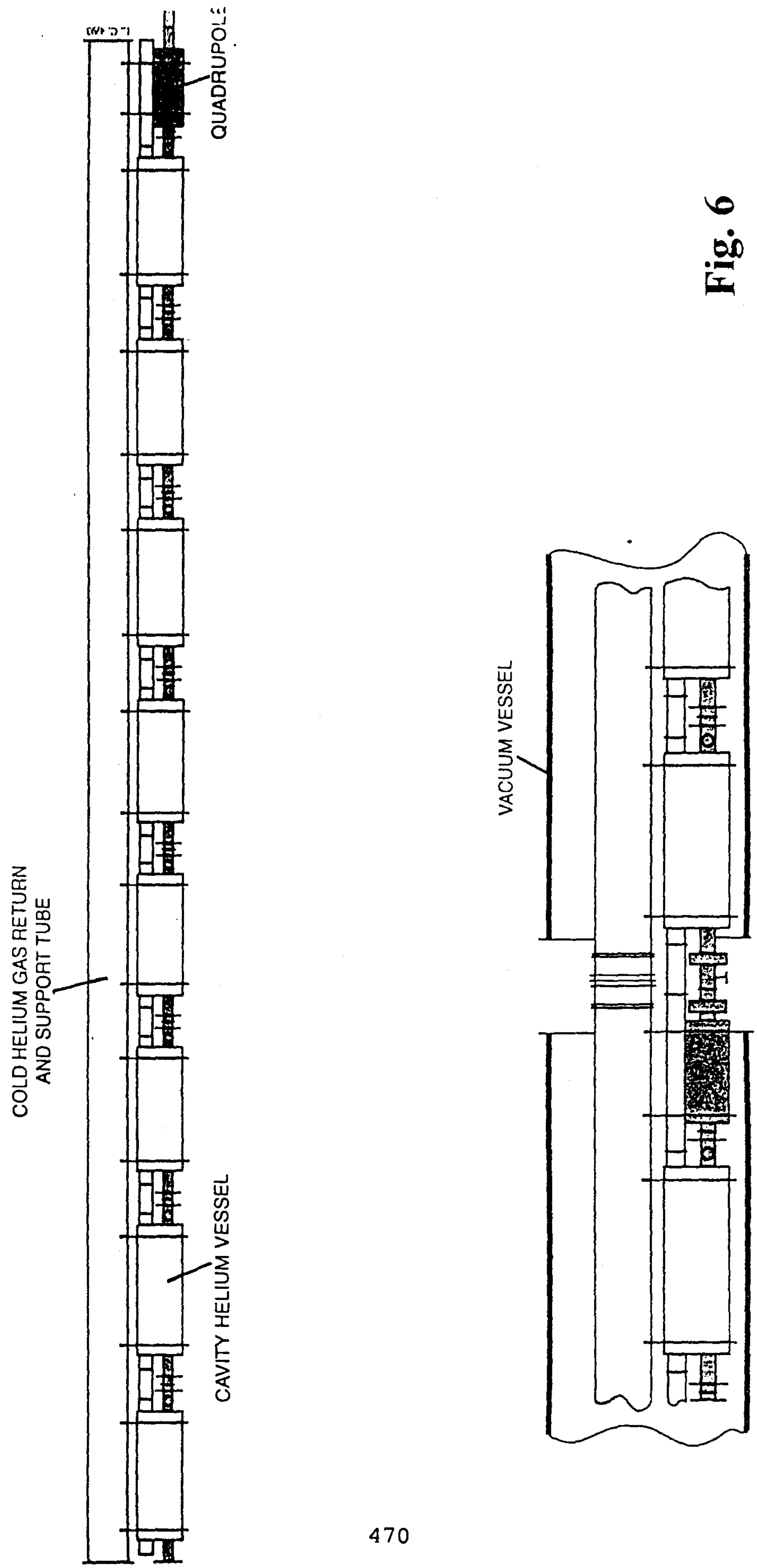
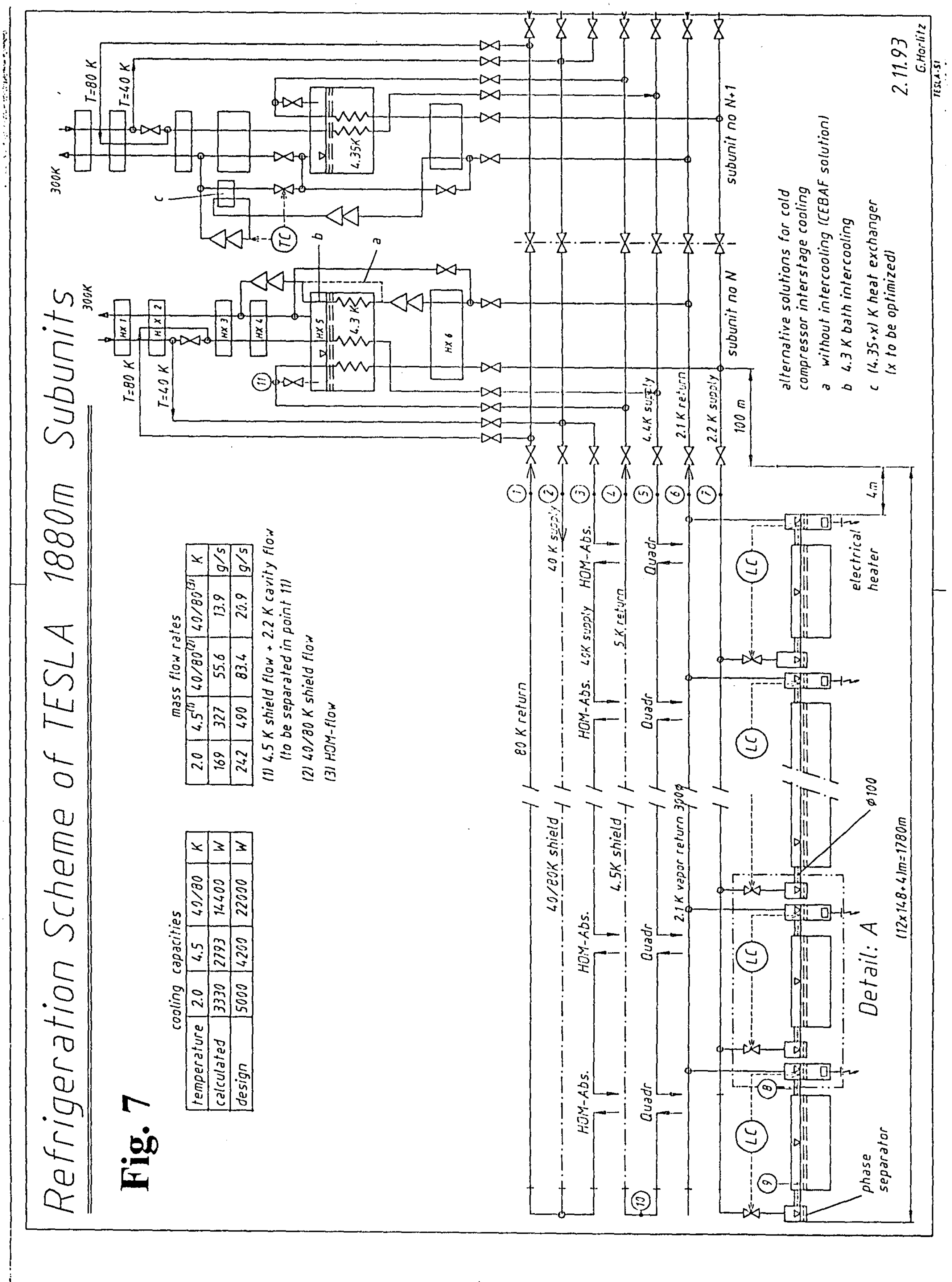

QUADRUPOLE
COLD HELIUM GAS RETURN AND SUPPORT TUBE
CAVITY HELIUM VESSEL
VACUUM VESSEL

Fig. 6



temperature	2.0	4.5	40/80	K
calculated	3330	2793	14400	W
design	5000	4200	22000	W

2.0	4.5[1]	40/80[2]	40/80[3]	K
169	327	55.6	13.9	g/s
242	490	83.4	20.9	g/s

DATUM: 4. 11. 1993

ANFANGSZEIT: 12 UHR 10 MIN 40 SEC

ENDZEIT: 12 UHR 27 MIN 44 SEC

DISTRIBUTION OF PRESSURES, TEMPERATURES AND HELIUM-LEVELS
IN A TESLA SUBUNIT OF 1880 m TOTAL LENGTH

PROGRAM "TESLA R" FROM NOVEMBER 3., 1993
FROM G.HORLITZ, DESY,HAMBURG/GERMANY

SUBUNIT-DIVISIONS ARE: 12 STRINGS OF 148.000 m
STRING -DIVISIONS ARE: 12 MODULES OF 12.200 m
MODULE -DIVISIONS ARE: 8 CAVITIES OF 1.384 m

SUMMARY OF RESULTS:
("CB" > COLDBOX-END; "FE" > FAR END OF SUBUNIT)

TOTAL HEAT-LOAD:	Q-tot= 3330.0 [W]	
MASS-FLOW-RATE SUPPLY:	MPS-CB = 0.1693 [kg/s]	
MASS-FLOW-RATE RETURN:	MPS-CB = 0.1691 [kg/s]	
SUPPLY-TUBE-PRESSURES:	PS-CB = 3.000 [bar]	PS-FE = 2.920 [bar]
SUPPLY-TUBE-TEMPERATURES:	TS-CB = 2.200 [K]	TS-FE = 2.951 [K]
RETURN-TUBE-PRESSURES:	PR-CB = 0.03291 [bar]	PR-FE = 0.03500 [bar]
RETURN-TUBE-TEMPERATURES:	TR-CB = 2.204 [K]	TR-FE = 2.039 [K]

CAVITY-HE-TEMPERATURES:

FE	TC-JT = 2.053 [K]	TC-OUT = 2.039 [K]
CB	TC-JT = 2.033 [K]	TC-OUT = 2.021 [K]

CAVITY-HE-PRESSURES:

FE	PCD-JT = 0.03639 [bar]	PCD-OUT = 0.03500 [bar]
CB	PCD-JT = 0.03445 [bar]	PCD-OUT = 0.03326 [bar]

STRING MASS-FLOW-RATES: MPS-CB = 0.01379 [kg/s] MPS-FE = 0.01486 [kg/s]

Fig. 8

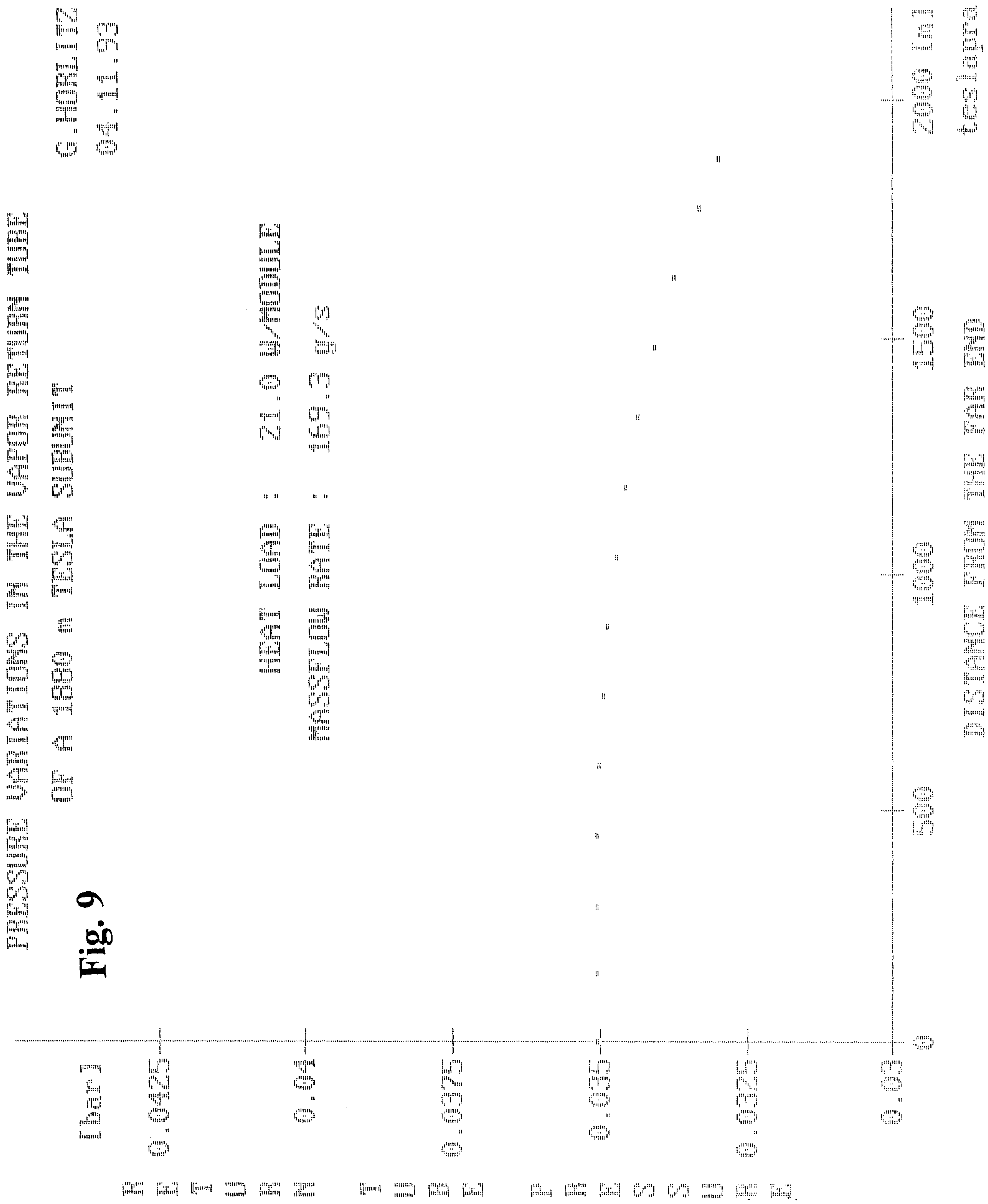
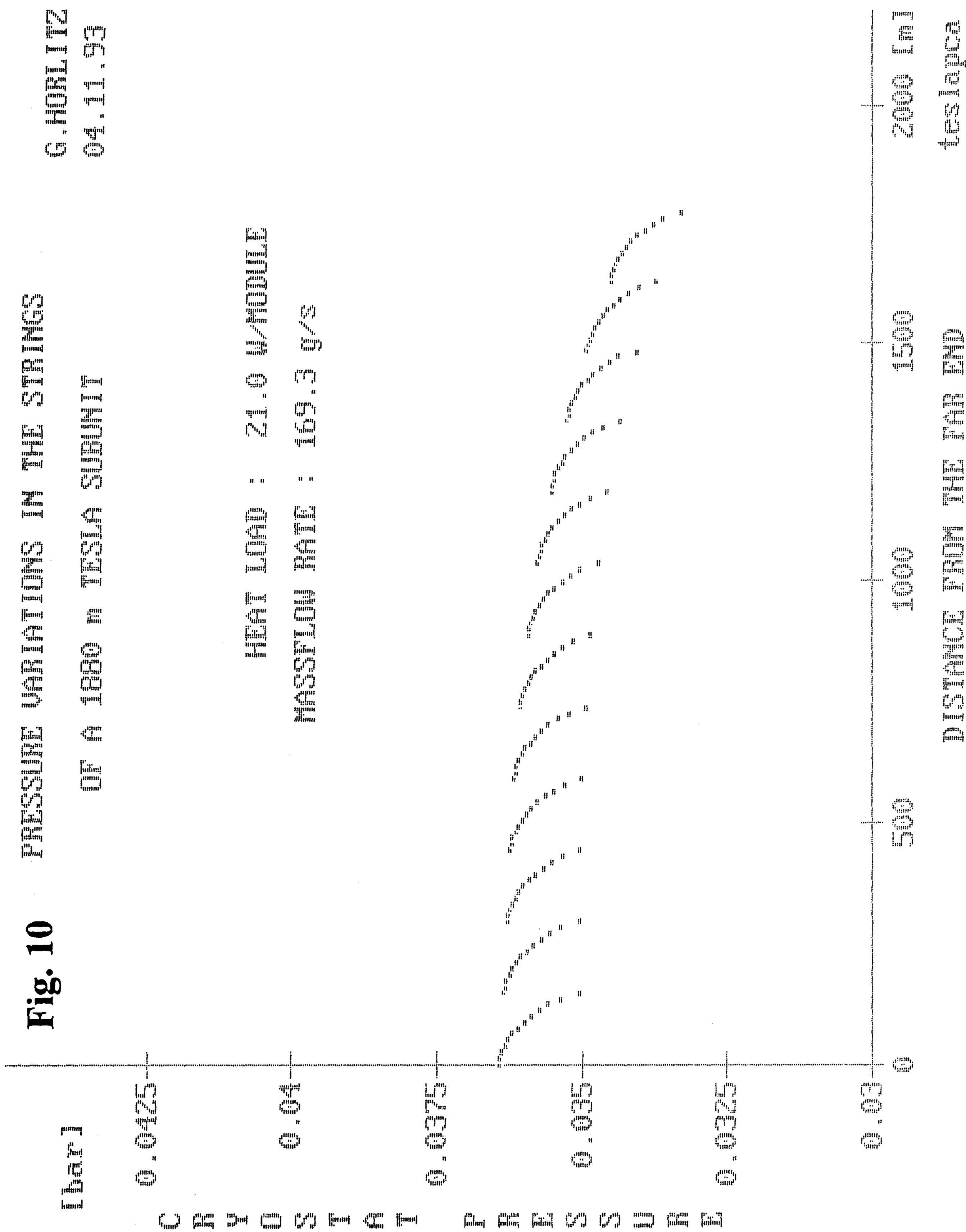

PRESSURE VARIATIONS IN THE VAPOR RETURN TUBE
OF A 1880 m TESLA SUBUNIT
G.HORLITZ
04.11.93
HEAT LOAD : 21.0 W/MODULE
MASSFLOW RATE : 169.3 G/S
DISTANCE FROM THE FAR END
[m]
0
500
1000
1500
2000
RETURN TUBE PRESSURE
[bar]
0.03
0.0325
0.035
0.0375
0.04
0.0425

Fig. 9

Fig. 10


PRESSURE VARIATIONS IN THE STRINGS
OF A 1880 m TESLA SUBUNIT
G.HORLITZ
04.11.93
HEAT LOAD : 21.0 W/MODULE
MASSFLOW RATE : 169.3 g/s
CRYOSTAT PRESSURE
[bar]
0.0425
0.04
0.0375
0.035
0.0325
0.03
0
500
1000
1500
2000 [m]
DISTANCE FROM THE WARM END

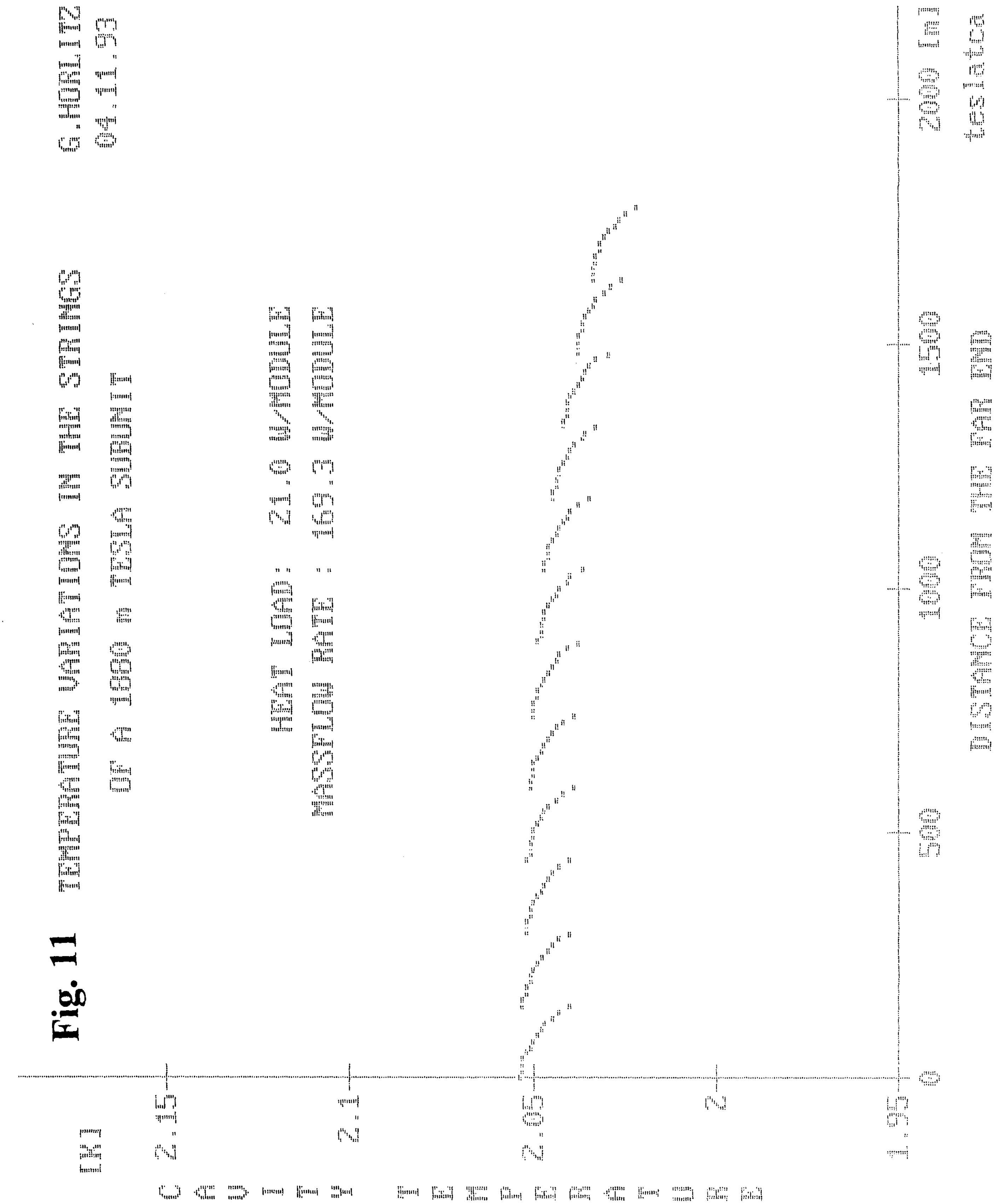

TEMPERATURE VARIATIONS IN THE STRINGS
OF A 1680 m TESLA SUBUNIT
G.HORLITZ
04.11.93
HEAT LOAD: 21.0 W/MODULE
MASSFLOW RATE: 169.3 W/MODULE
CAVITY TEMPERATURE
[K]
2.15
2.1
2.05
2
1.95
0
500
1000
1500
2000 [m]
DISTANCE FROM THE HOT END

Fig. 11

```
DATUM:  4. 11. 1993

        ANFANGSZEIT: 13 UHR   5 MIN  36 SEC

        ENDZEIT: 13 UHR  22 MIN  39 SEC

                  DISTRIBUTION OF PRESSURES, TEMPERATURES AND HELIUM-LEVELS
                     IN A TESLA SUBUNIT OF 1880 m TOTAL LENGTH

                  PROGRAM "TESLA R" FROM NOVEMBER 3., 1993
                  FROM G.HORLITZ, DESY,HAMBURG/GERMANY

             SUBUNIT-DIVISIONS ARE:  12 STRINGS OF 148.000 m
             STRING -DIVISIONS ARE:  12 MODULES OF  12.200 m
             MODULE -DIVISIONS ARE:   8 CAVITIES OF  1.384 m

                        SUMMARY OF RESULTS:
             ("CB" > COLDBOX-END; "FE" > FAR END OF SUBUNIT)

        TOTAL HEAT-LOAD:            Q-tot=   4842.0 [W]

        MASS-FLOW-RATE SUPPLY:    MPS-CB =   0.2445 [kg/s]

        MASS-FLOW-RATE RETURN:    MPS-CB =   0.2443 [kg/s]

        SUPPLY-TUBE-PRESSURES:     PS-CB =   3.000 [bar]        PS-FE =   2.835 [bar]

        SUPPLY-TUBE-TEMPERATURES:  TS-CB =   2.200 [K]          TS-FE =   2.753 [K]

        RETURN-TUBE-PRESSURES:     PR-CB = 0.03064 [bar]        PR-FE = 0.03500 [bar]

        RETURN-TUBE-TEMPERATURES:  TR-CB =   2.138 [K]          TR-FE =   2.039 [K]

        CAVITY-HE-TEMPERATURES:
                  FE     TC-JT =   2.064 [K]         TC-OUT =   2.039 [K]

                  CB     TC-JT =   2.027 [K]         TC-OUT =   2.001 [K]

        CAVITY-HE-PRESSURES:
                  FE     PCD-JT = 0.03755 [bar]        PCD-OUT = 0.03500 [bar]

                  CB     PCD-JT = 0.03385 [bar]        PCD-OUT = 0.03140 [bar]

        STRING MASS-FLOW-RATES:   MPS-CB = 0.02014 [kg/s]     MPS-FE = 0.02109 [kg/s]
```

Fig. 12

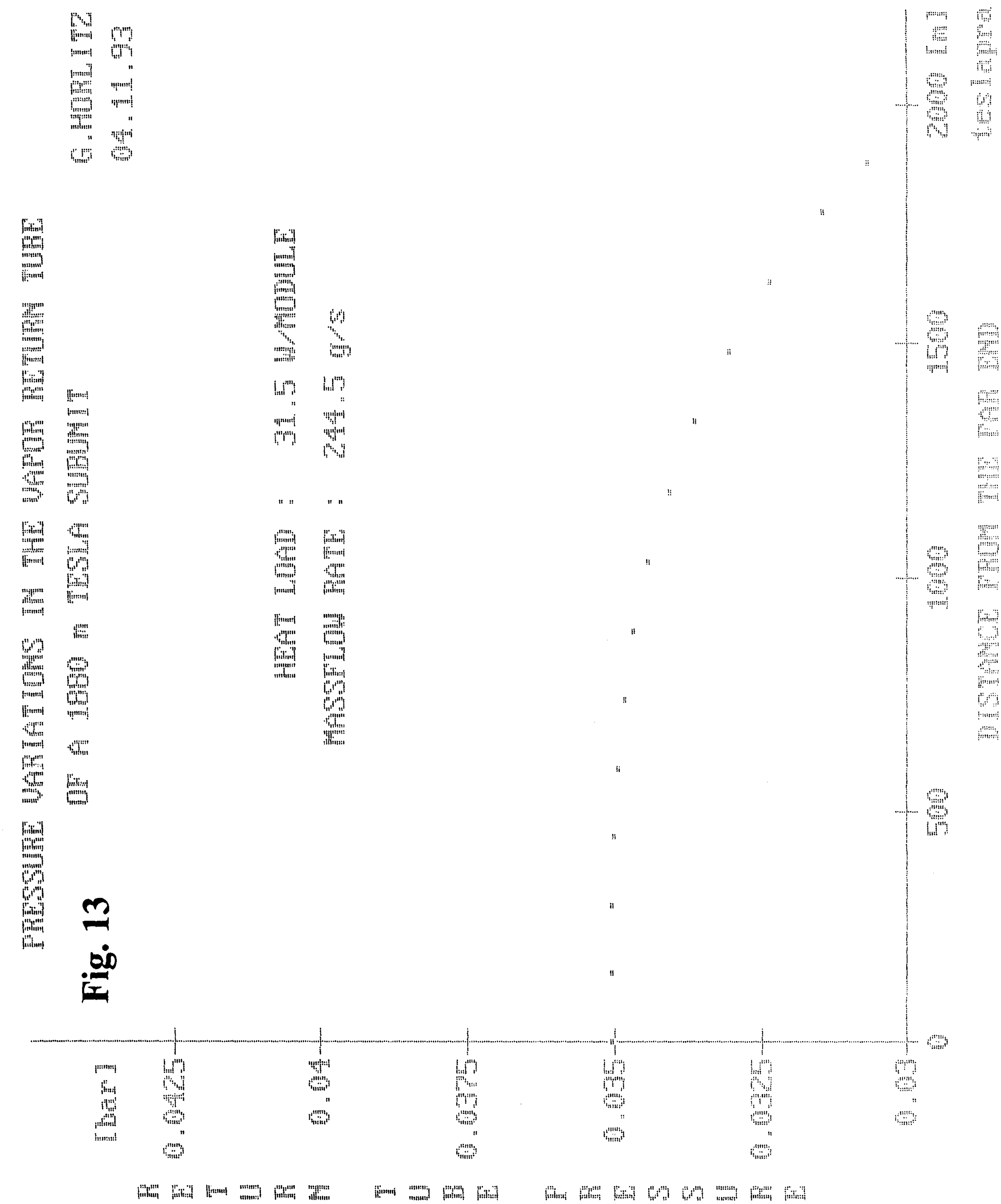

PRESSURE VARIATIONS IN THE VAPOR RETURN TUBE
OF A 1880 m TESLA SUBUNIT
G. HORLITZ
04.11.93
HEAT LOAD : 31.5 W/MODULE
MASSFLOW RATE : 244.5 G/S
[bar]
0.0425
0.04
0.0375
0.035
0.0325
0.03
RETURN TUBE PRESSURE
0
500
1000
1500
2000 [m]
DISTANCE FROM THE TAP END
test end

Fig. 13

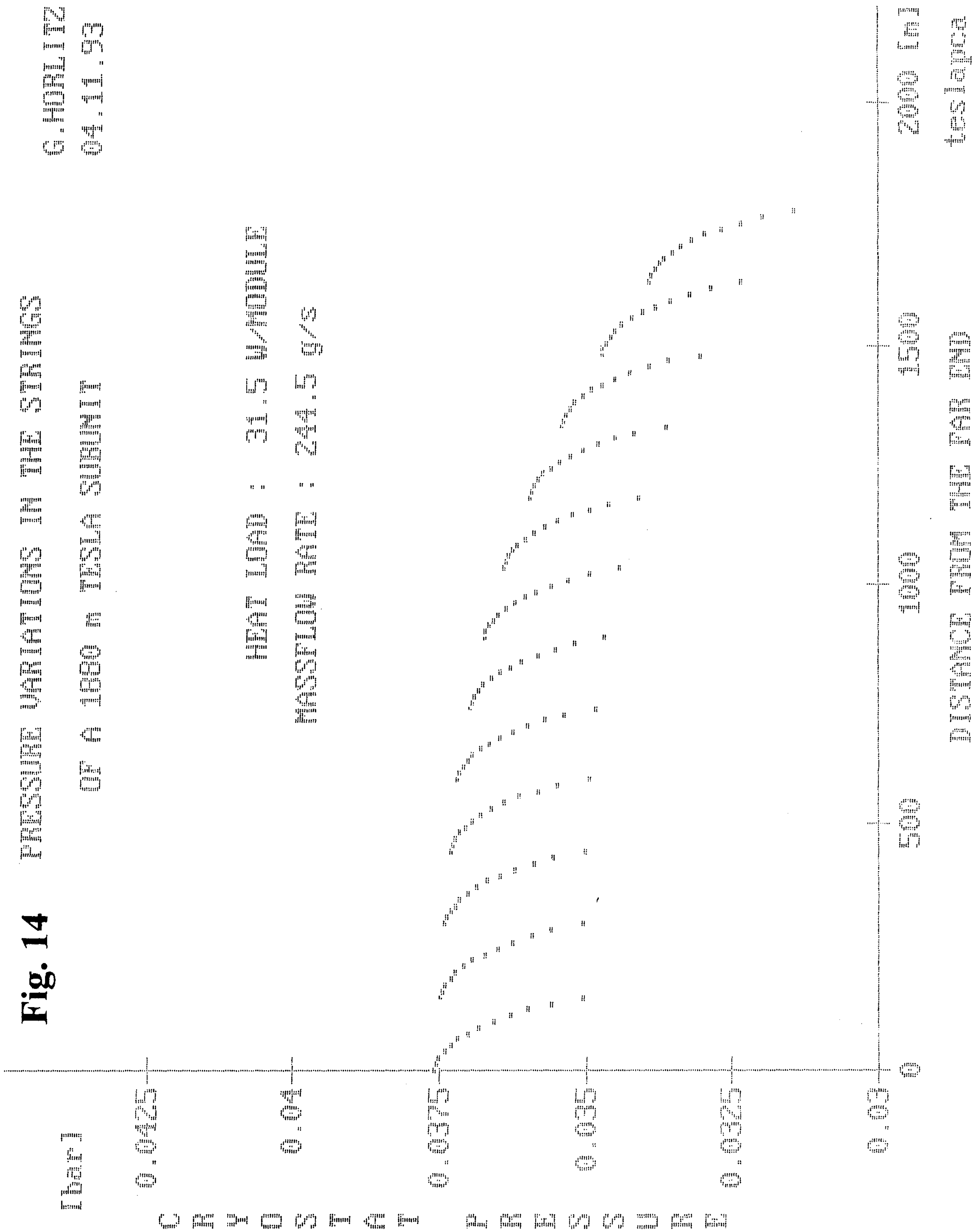

PRESSURE VARIATIONS IN THE STRINGS
OF A 1880 m TESLA SUBUNIT
HEAT LOAD : 31.5 W/MODULE
MASSFLOW RATE : 244.5 G/S
G.HORLITZ
04.11.93
0
500
1000
1500
2000 [m]
DISTANCE FROM THE FAR END
0.03
0.0325
0.035
0.0375
0.04
0.0425
[bar]
CRYOGENIC PRESSURE

Fig. 14

Fig. 15

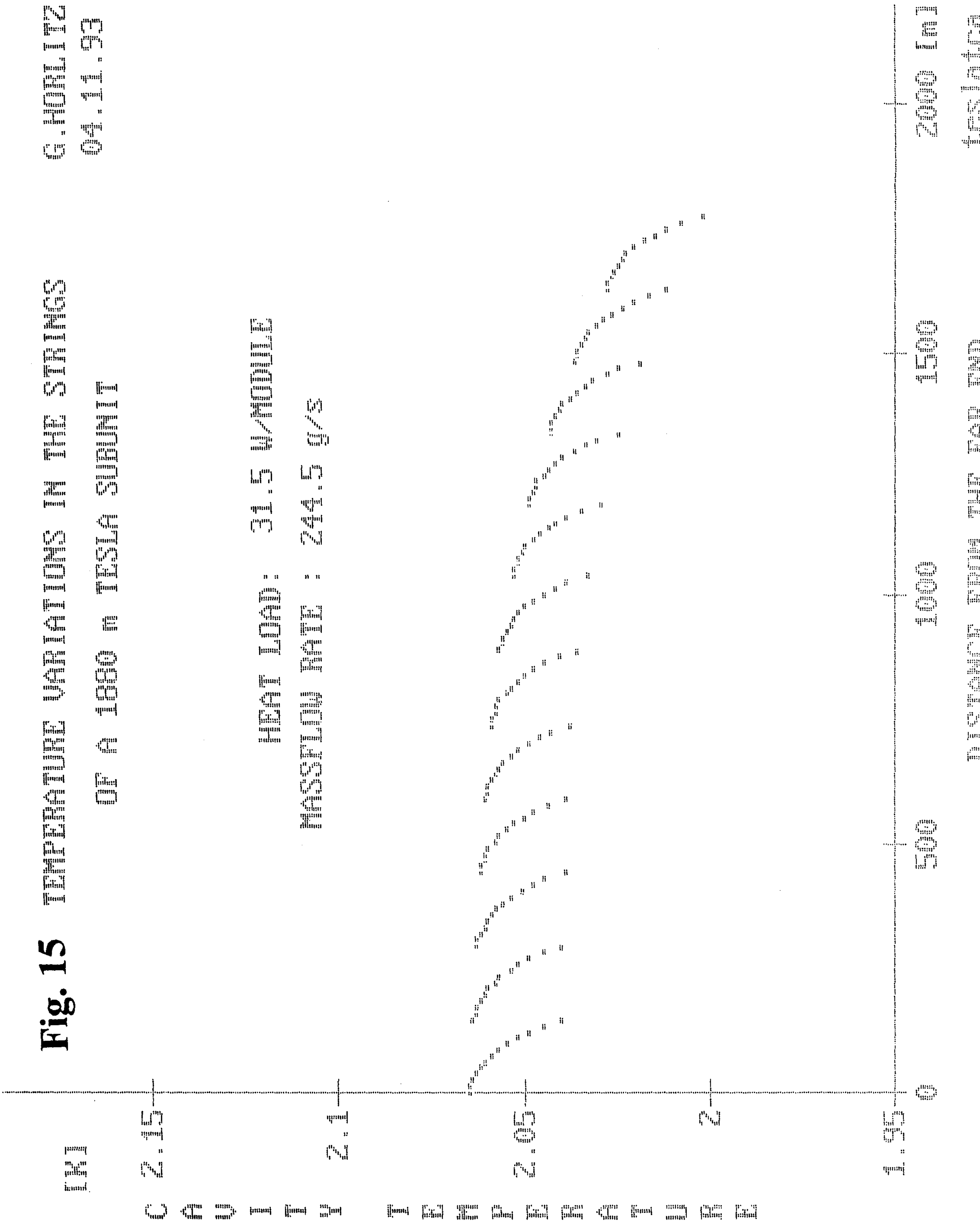
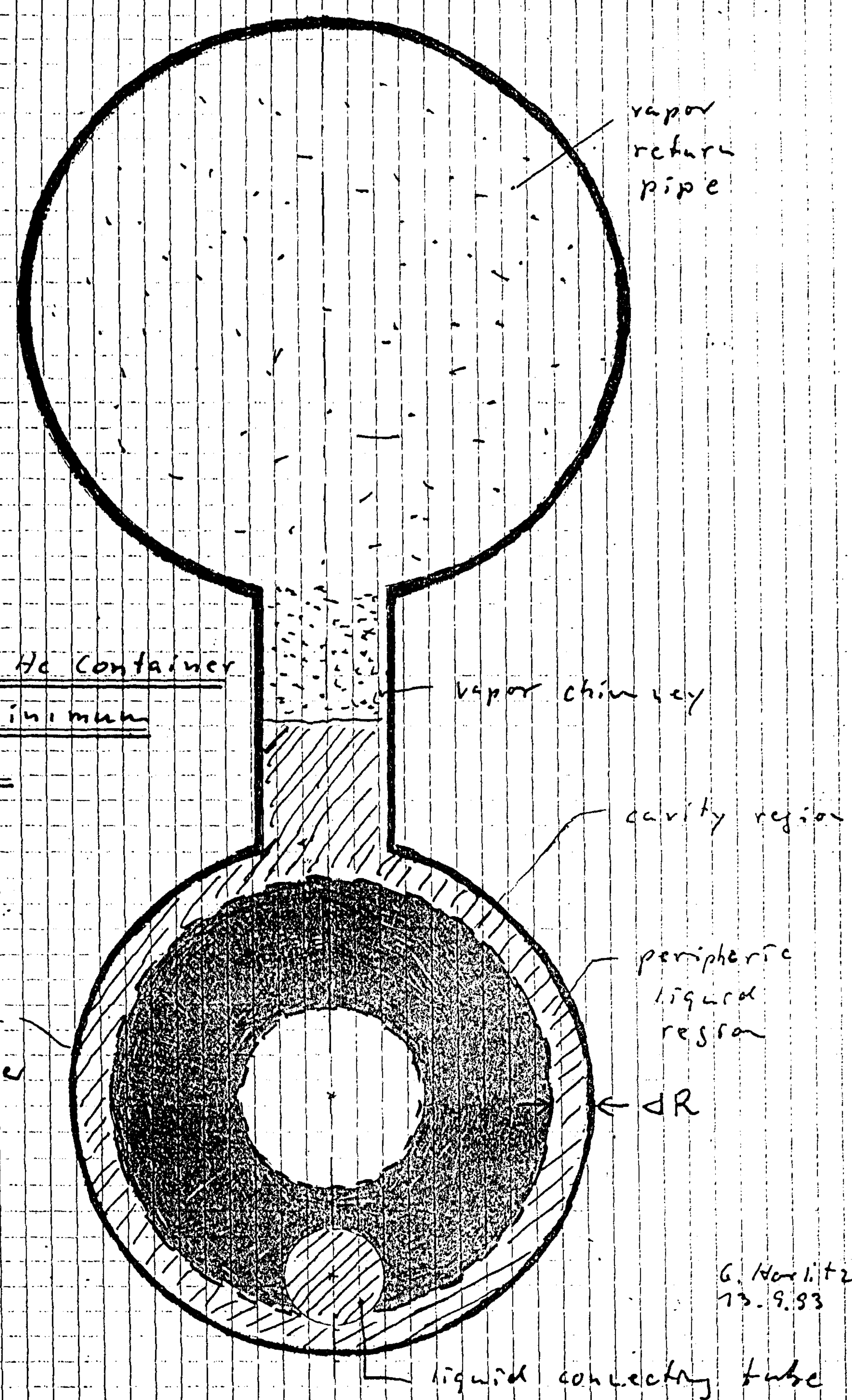

TEMPERATURE VARIATIONS IN THE STRINGS
OF A 1880 m TESLA SUBUNIT
G. HORLITZ
04.11.93
HEAT LOAD : 31.5 W/MODULE
MASSFLOW RATE : 244.5 G/S
DISTANCE FROM THE FAR END
[m]
0
500
1000
1500
2000
[K]
1.95
2
2.05
2.1
2.15
CAVITY TEMPERATURE

Fig. 16

TESLA He container with minimum Volume



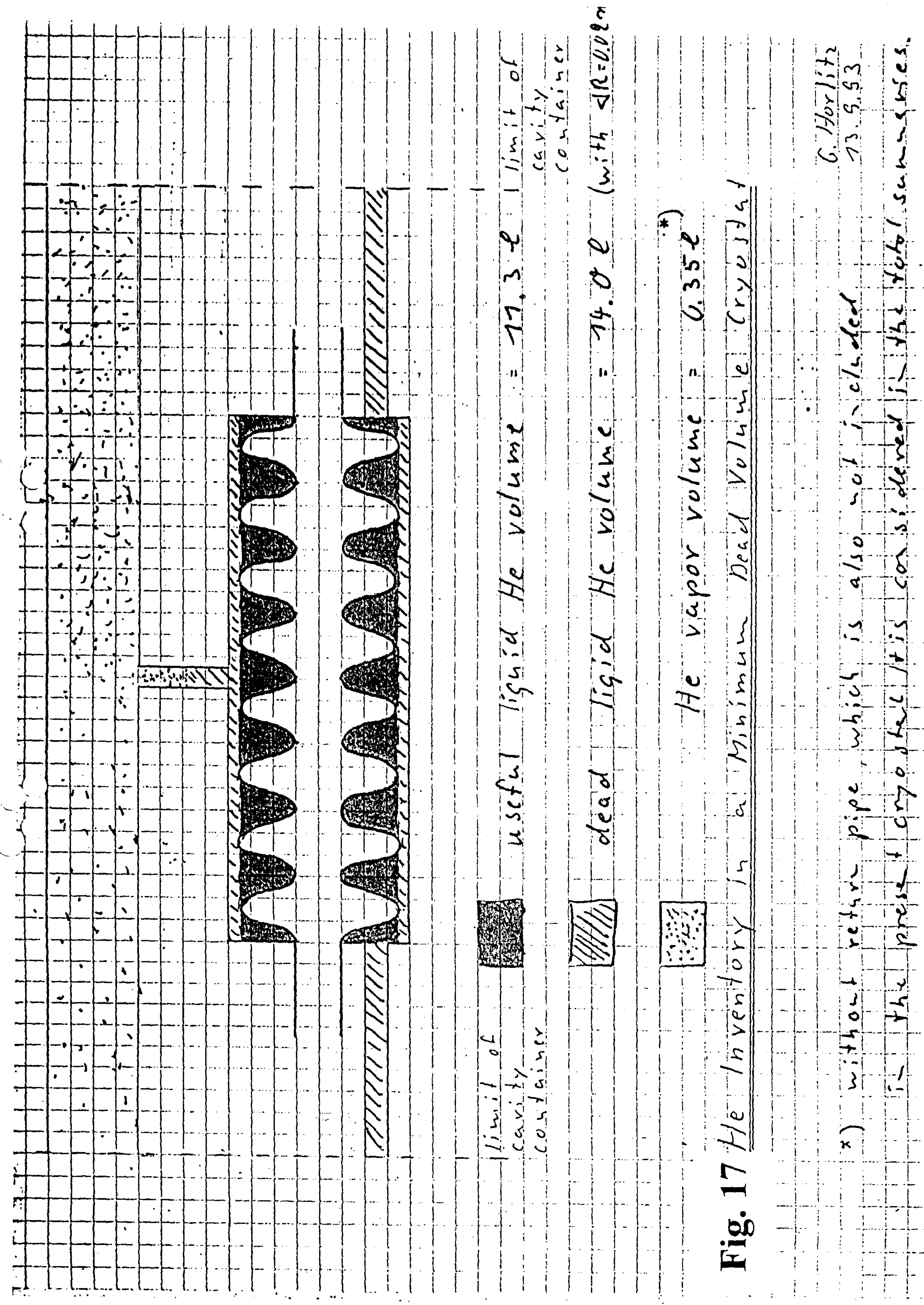


Fig. 17 He Inventory in a Minimum Dead Volume Cryostat

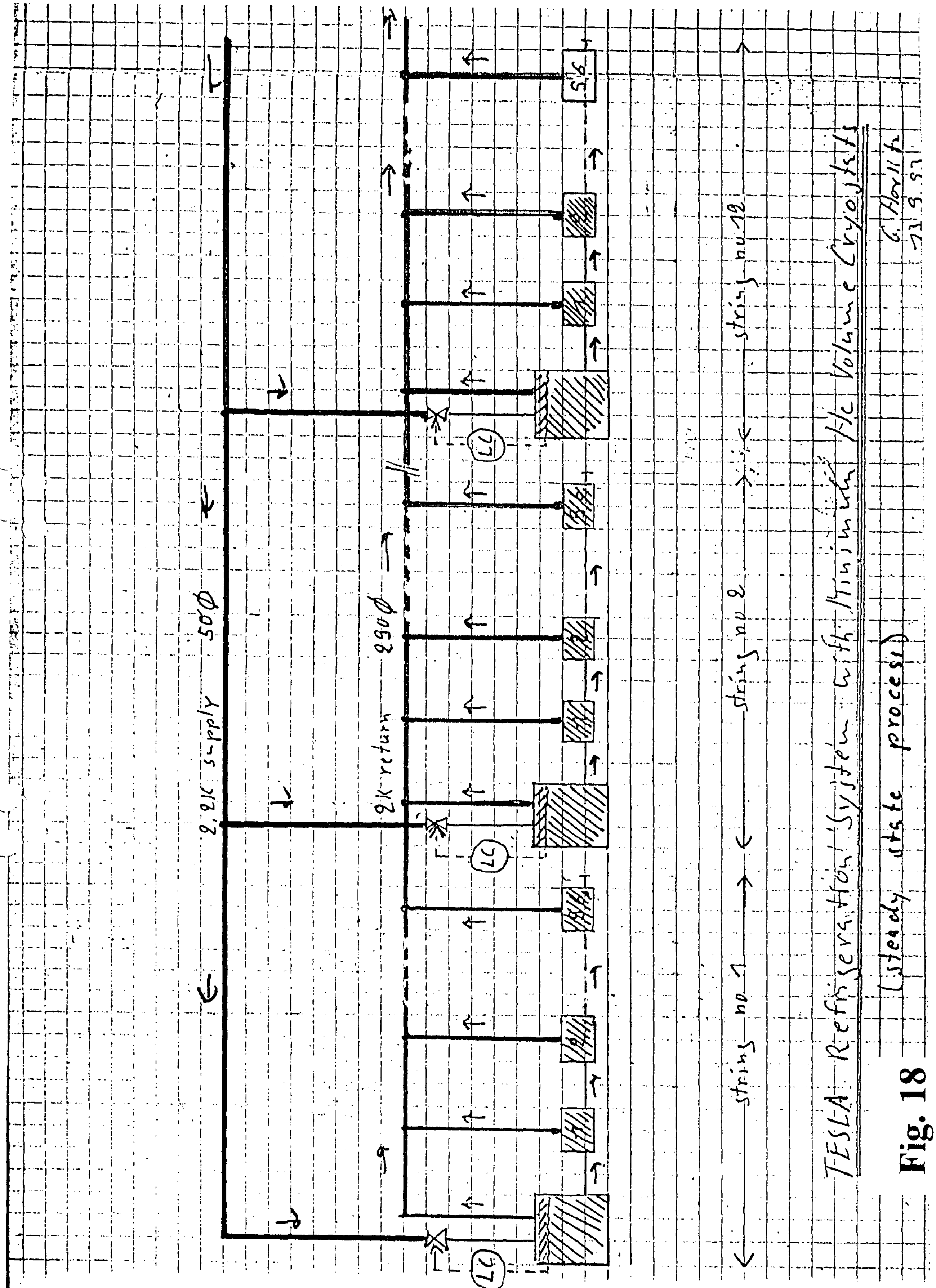

2.2K supply
2K return
string no 1
string no 2
string no 12
LC
TESLA Refrigeration System with Minimum He Volume Cryostats
(steady state process)

Fig. 18

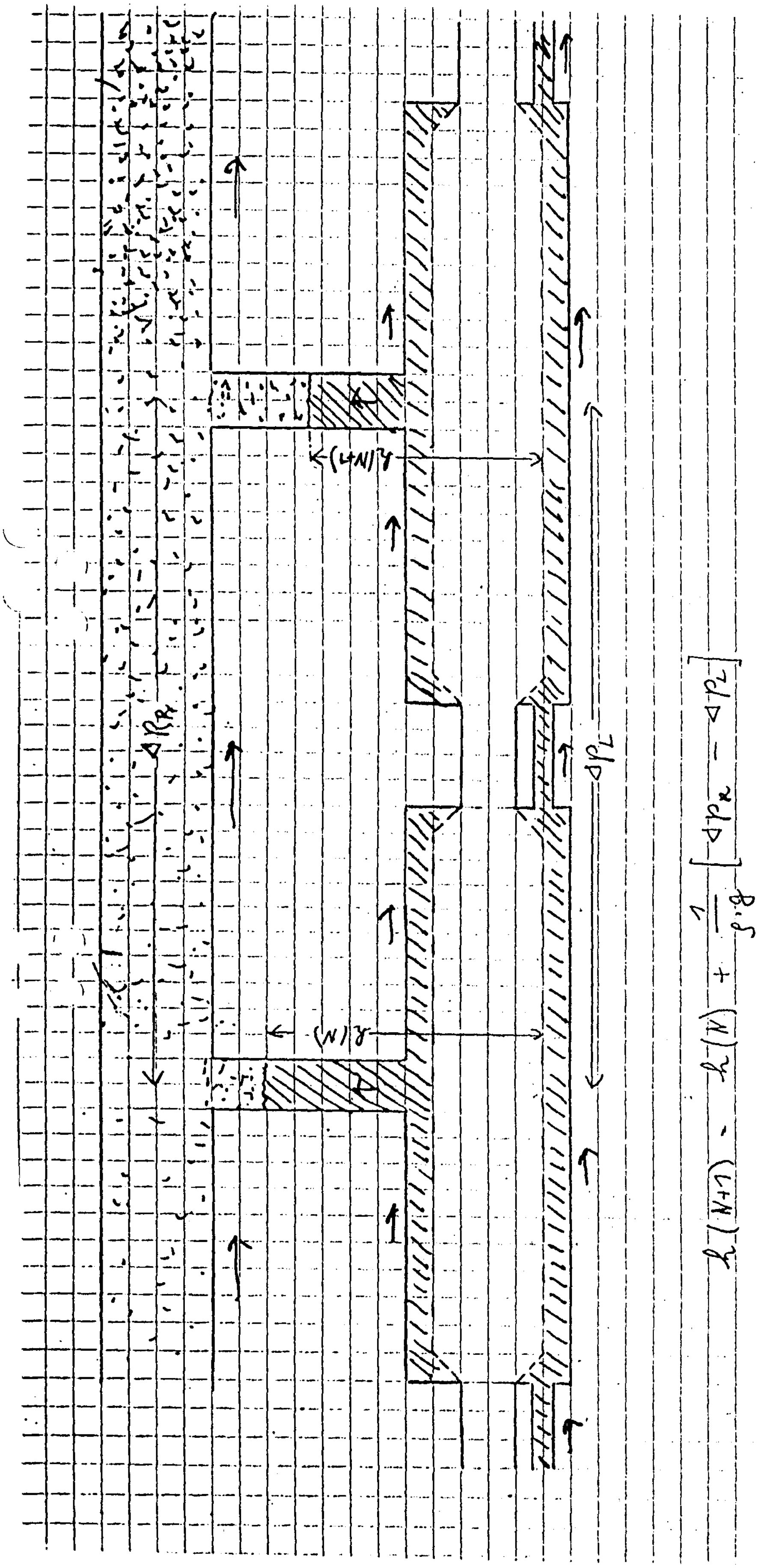


Fig. 19 Calculation of He Levels in Adjacent Cryostats

G. Horlitz
23.9.93

DATUM: 4. 11. 1993

ANFANGSZEIT: 19 UHR 39 MIN 53 SEC

ENDZEIT: 19 UHR 44 MIN 23 SEC

DISTRIBUTION OF PRESSURES, TEMPERATURES AND HELIUM-LEVELS
IN A TESLA SUBUNIT OF 1880 m TOTAL LENGTH
WITH CAVITY-HE-VESSELS OF MINIMUM SIZE DIRECTLY CONNECTED TO THE 2K GAS-RETURN-TUBE

PROGRAM "TESLA Y" FROM AUGUST, 22, 1993
FROM G.HORLITZ, DESY,HAMBURG/GERMANY

SUBUNIT-DIVISIONS ARE: 12 STRINGS OF 148.000 m
STRING -DIVISIONS ARE: 12 MODULES OF 12.200 m
MODULE -DIVISIONS ARE: 12 CAVITIES OF 1.384 m

SUMMARY OF RESULTS:
("CB" > COLDBOX-END; "FE" > FAR END OF SUBUNIT)

TOTAL HEAT-LOAD:	Q-tot= 4830.0 [W]		
MASS-FLOW-RATE SUPPLY:	MPS-CB = 0.2430 [kg/s]		
MASS-FLOW-RATE RETURN:	MPS-CB = 0.2430 [kg/s]		
SUPPLY-TUBE-PRESSURES:	PS-CB = 3.000 [bar]	PS-FE = 2.837 [bar]
SUPPLY-TUBE-TEMPERATURES:	TS-CB = 2.200 [K]	TS-FE = 2.756 [K]
RETURN-TUBE-PRESSURES:	PR-CB = 0.03086 [bar]	PR-FE = 0.03500 [bar]
RETURN-TUBE-TEMPERATURES:	TR-CB = 2.064 [K]	TR-FE = 2.039 [K]
CAVITY-HE-TEMPERATURES:	TC-CB = 1.997 [K]	TC-FE = 2.039 [K]
STRING MASS-FLOW-RATES:	MPS-CB = 0.02001 [kg/s]	MPS-FE = 0.02099 [kg/s]

Fig. 20

Fig. 21

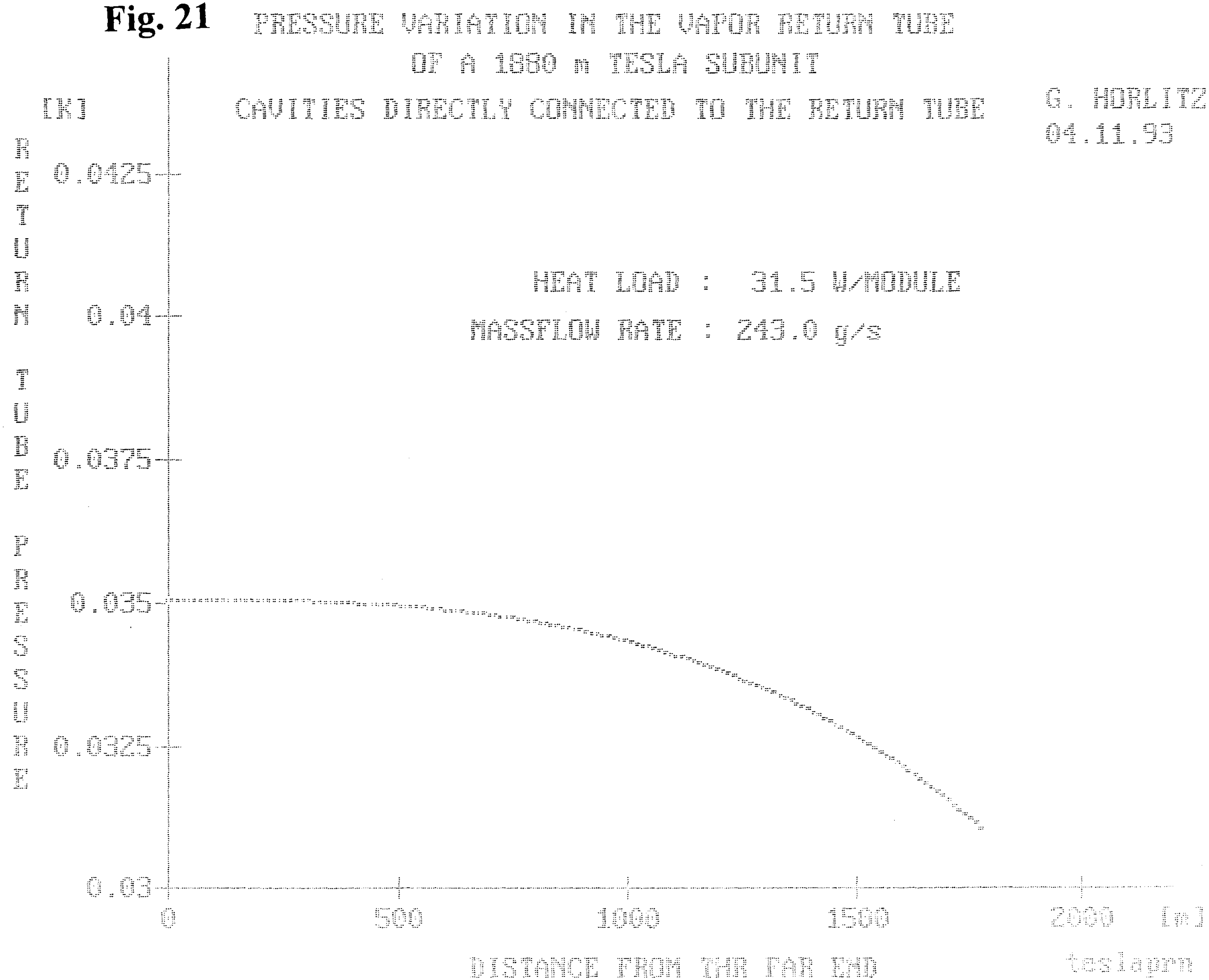
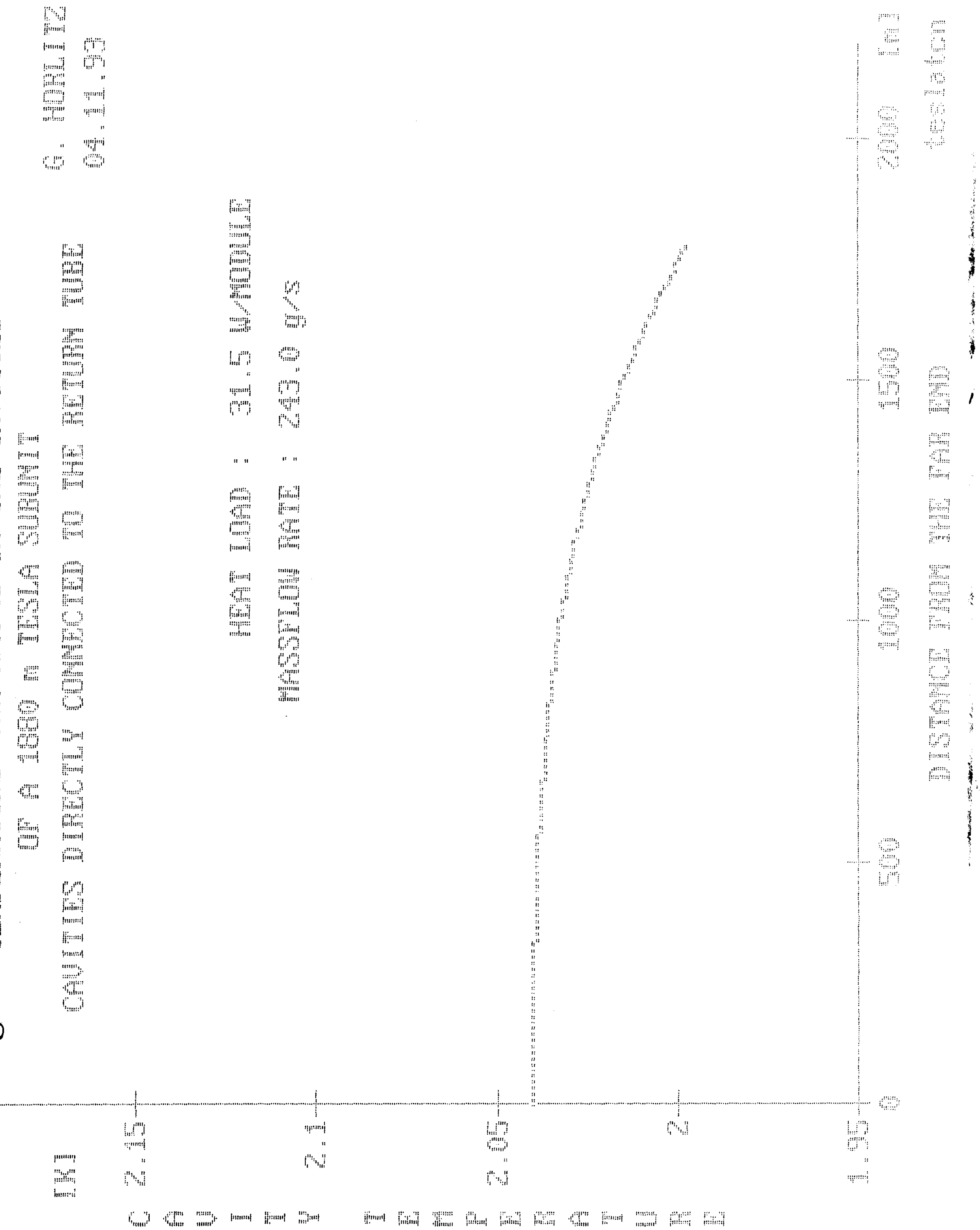

PRESSURE VARIATION IN THE VAPOR RETURN TUBE
OF A 1880 m TESLA SUBUNIT
CAVITIES DIRECTLY CONNECTED TO THE RETURN TUBE
G. HORLITZ
04.11.93
[K]
RETURN TUBE PRESSURE
0.0425
0.04
0.0375
0.035
0.0325
0.03
HEAT LOAD : 31.5 W/MODULE
MASSFLOW RATE : 243.0 g/s
0
500
1000
1500
2000
[m]
DISTANCE FROM THR FAR END
teslaprn

Fig. 22


TEMPERATURE VARIATIONS IN THE CAVITIES
OF A 1880 m TESLA SUBUNIT
CAVITIES DIRECTLY CONNECTED TO THE RETURN TUBE
G. HORLITZ
04.11.93
HEAT LOAD : 31.5 W/MODULE
MASSFLOW RATE : 243.0 G/S
CAVITY TEMPERATURE
[K]
2.15
2.1
2.05
2
1.95
0
500
1000
1500
2000
[m]
DISTANCE FROM THE FAR END

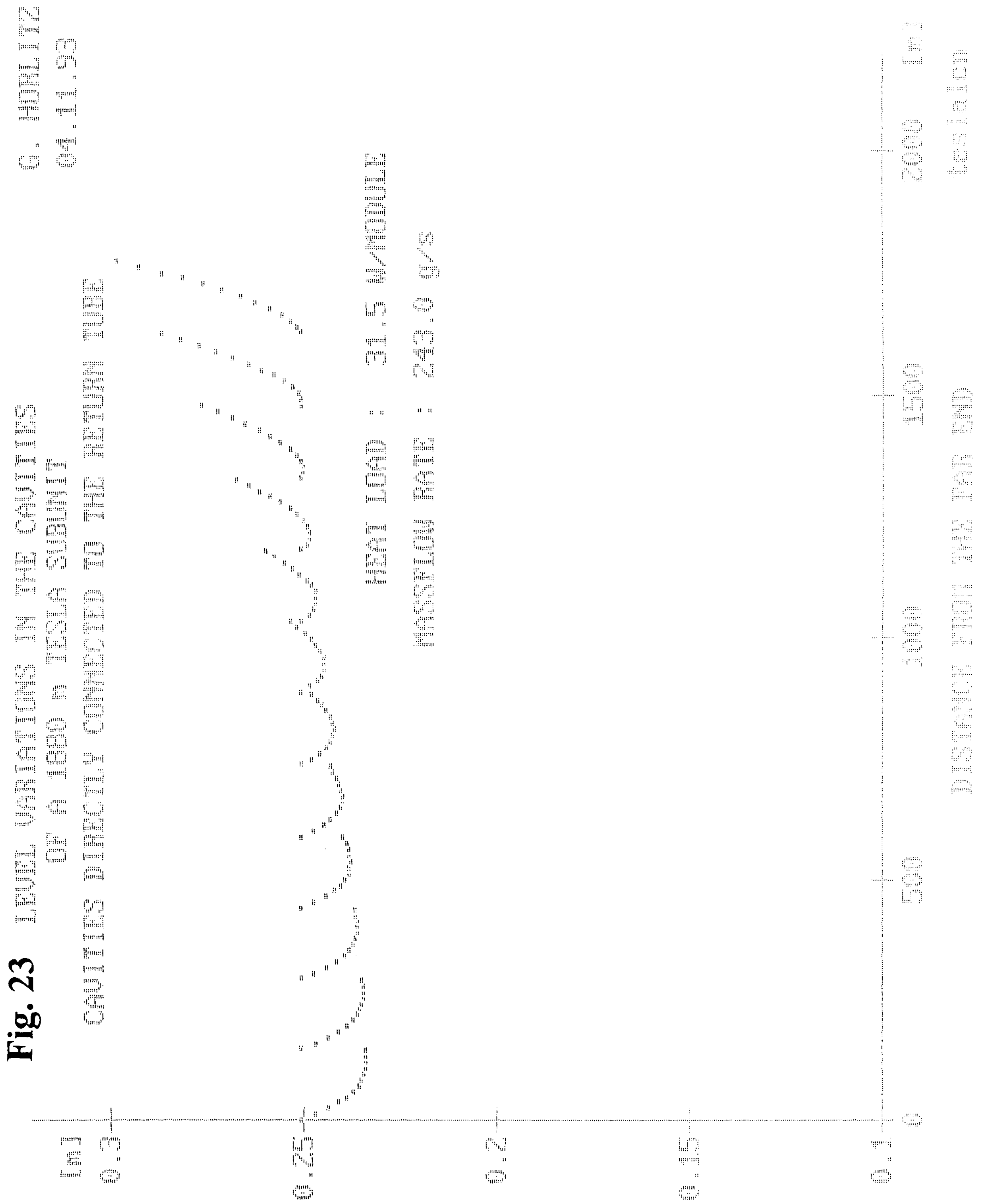

LEVEL VARIATIONS IN THE CAVITIES
OF A 1680 m TESLA SUBUNIT
CAVITIES DIRECTLY CONNECTED TO THE RETURN TUBE
G. HORLITZ
04.11.93
HEAT LOAD : 31.5 W/MODULE
MASSFLOW RATE : 243.0 G/S
[m]
0.3
0.25
0.2
0.15
0.1
LEVEL HEIGHT
0
500
1000
1500
2000
[m]
DISTANCE FROM THE GAS RETURN END

Fig. 23

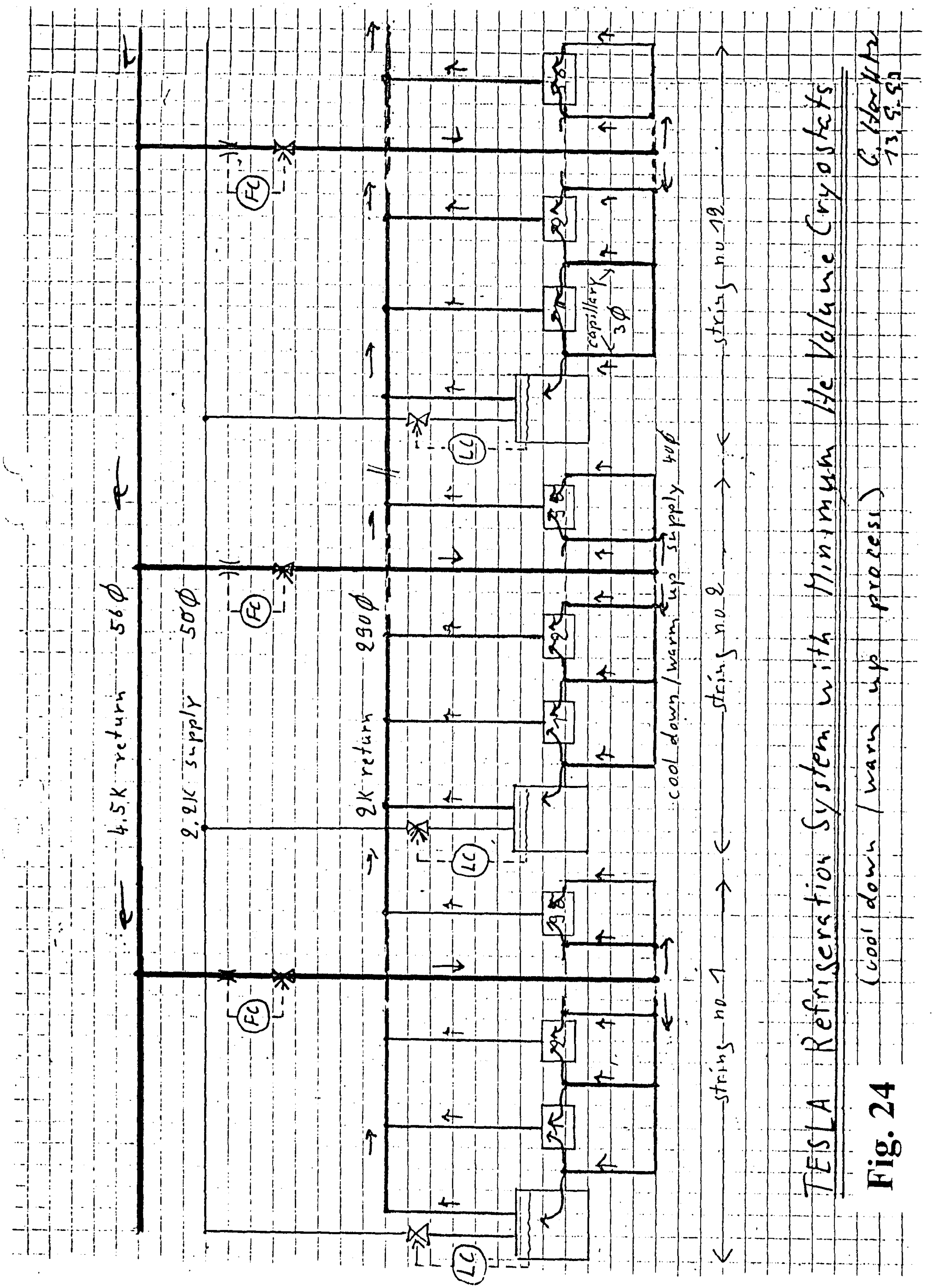

TESLA Refrigeration System with Minimum He Volume Cryostats
(cool down / warm up process)
4.5K return 56⌀
2.2K supply 50⌀
2K return 290⌀
cool down / warm up supply 40⌀
string no 1
string no 2
string no 12
capillary 3⌀
FC
FC
FC
LC
LC
LC

Fig. 24

Fig. 25 COOL DOWN OF ONE TESLA CAVITY

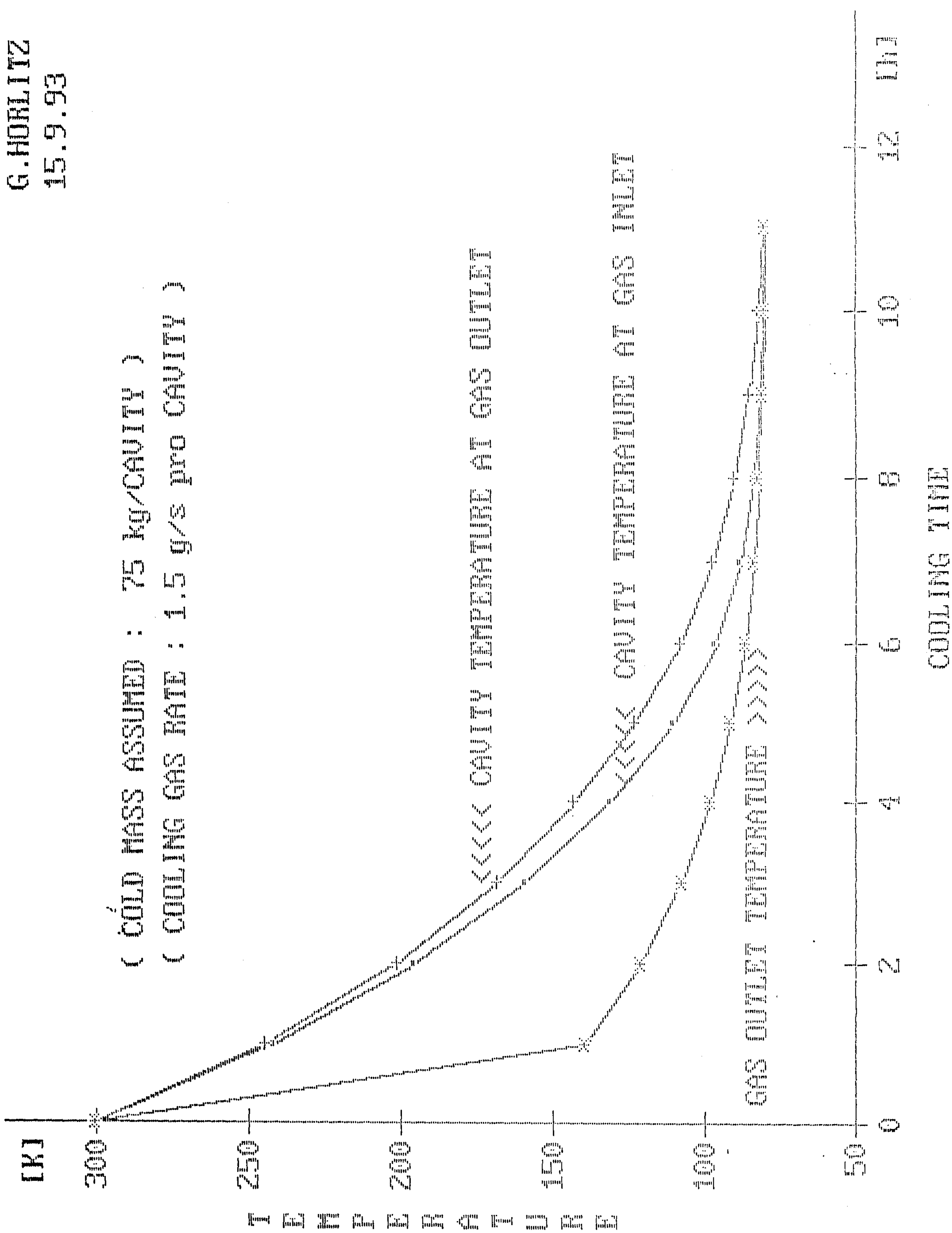
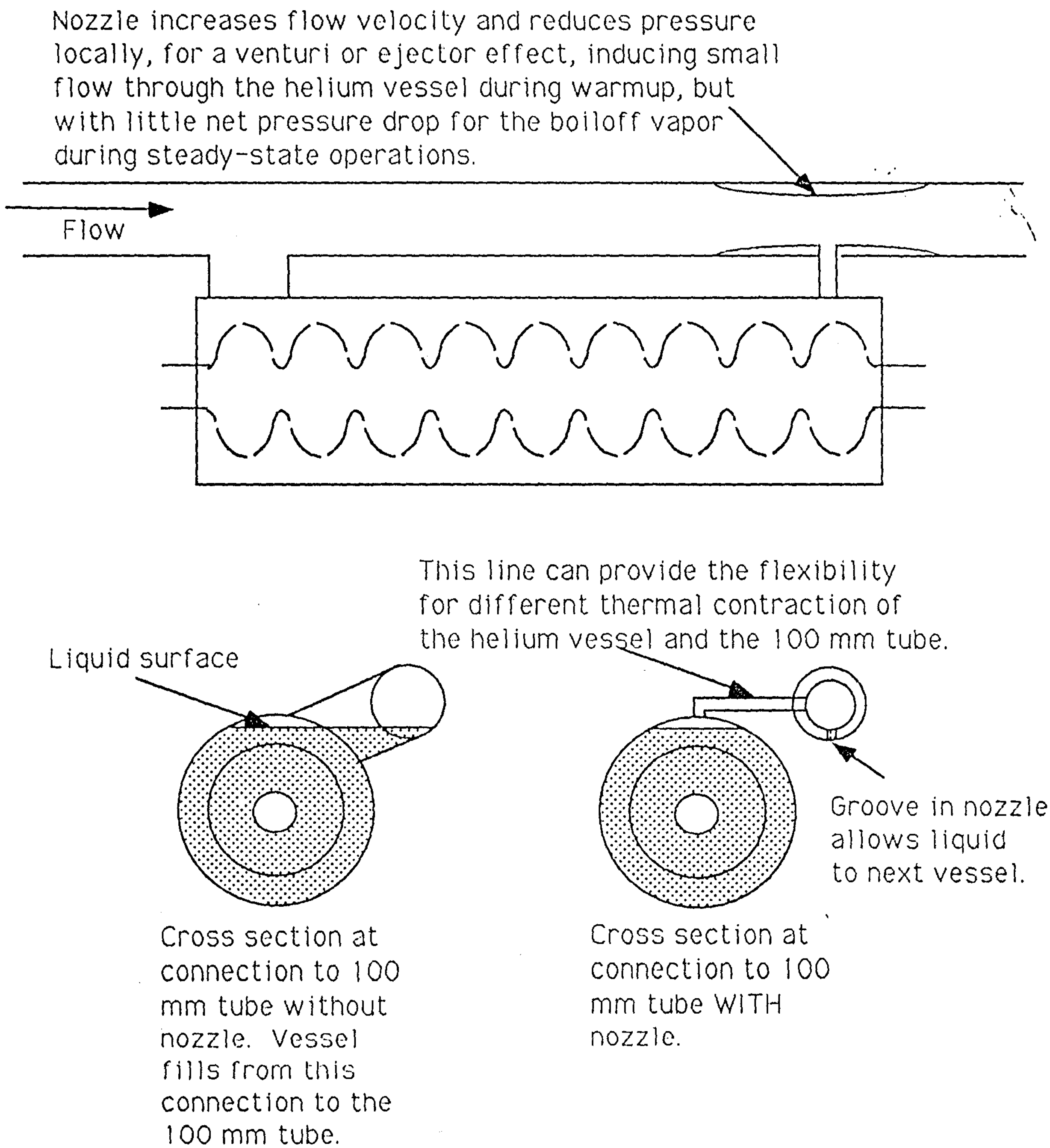
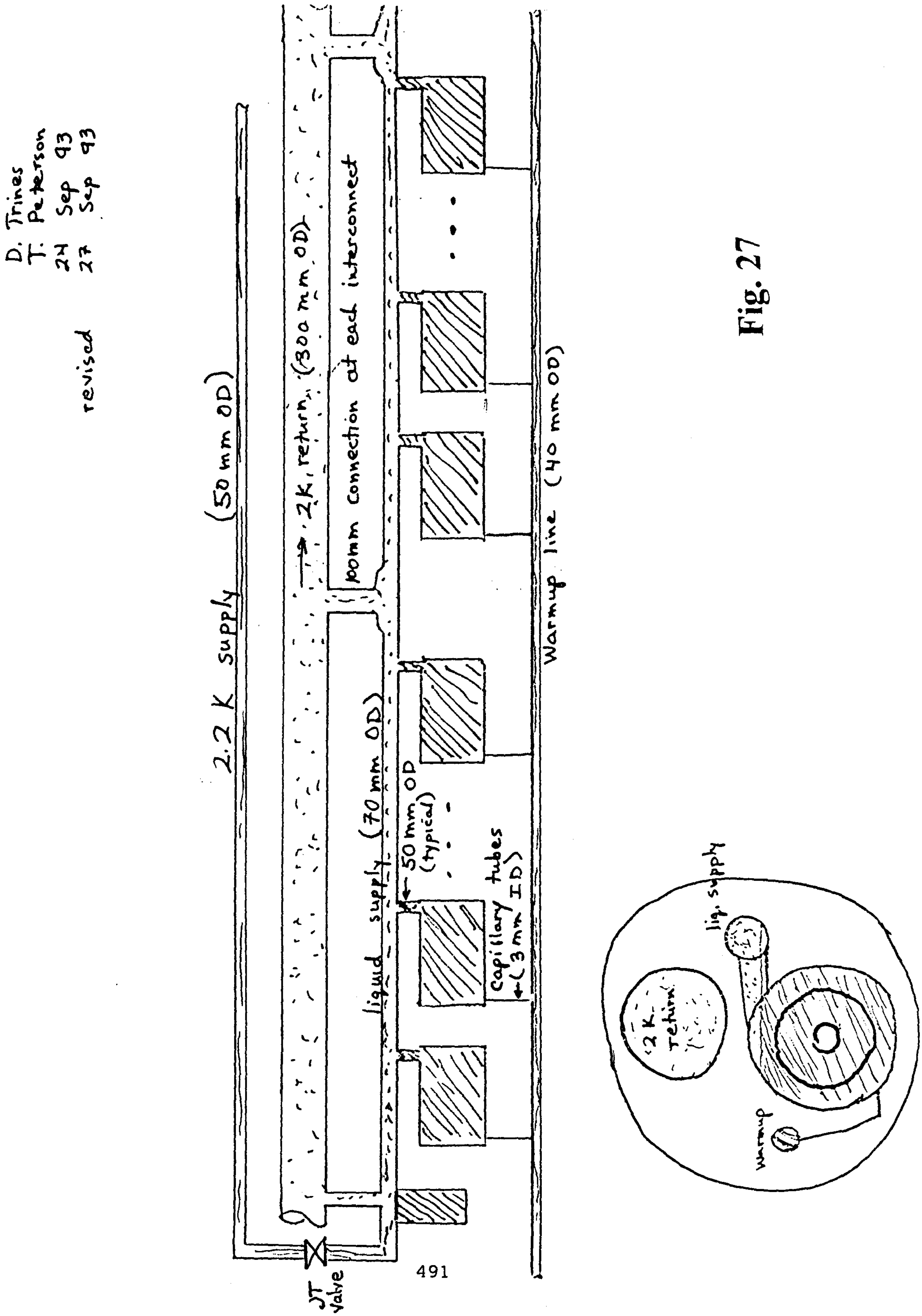


Fig. 26

Flow Inducer for Helium Gas Warmup
in a Reduced Inventory Helium Vessel





D. Trines
T. Peterson
24 Sep 93
27 Sep 93
revised
2.2 K supply (50 mm OD)
2K, return, (300 mm OD)
100mm connection at each interconnect
liquid supply (70 mm OD)
50 mm OD (typical)
capillary tubes (3 mm ID)
Warmup line (40 mm OD)
JT Valve
2K return
liq. supply
warmup

Fig. 27