CRYOGENICS FOR SUPERCONDUCTING RF CAVITIES IN LEP

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1. Introduction

The CERN Research and Development Programme on superconducting RF cavities is planned to culminate in a test of a significant number of such cavities in LEP immediately after start-up of the machine with classical copper cavities. My intention is to summarize work on cryogenics in connection with the test. This work is currently under way at CERN and in industry and mainly concerned with the development of a powerful but compact refrigerator suitable for installation in the LEP tunnel and with the design of cryostats for the cavities. My collegues and I are fully aware of the fact that intensive work will be required in the near future by many other cryogenic problems, about which I will not talk now because our view on them is not yet sufficiently clear. We are confident that they can be solved in due course. Thus the problems of compressors, of transfer lines, of helium storage and purification and of emergency situations, e.g. safe helium discharge in case of sudden heat surges, are not discussed.

2. Compact refrigerator

The people mainly involved in the development of the refrigerator concept were F.Birchler, M.Firth, M.Morpurgo, F.Schmeissner and myself. We started from the assumption that the refrigerator cold boxes will be installed in the klystron tunnels adjacent to the beam tunnel straight sections ('RF tunnels') in which the superconducting cavities are located, while the compressors will be housed at ground level. An alternative installation of the cold boxes at ground level is worth consideration, but thermodynamic, technical and economic problems of the complex transfer line system then required are very serious.

In the following, the term 'refrigerator' is meant to design the refrigerator components located underground, essentially the cold box(es) and ancillary equipment.

The topology of the LEP RF and klystron tunnels is shown in Fig.1. Each RF station comprises seven 'half cells' (sections between quadrupoles) of the machine lattice. Four of them will be used for copper cavities, one might be used later on for a higher harmonic RF system, and two half cells (the ones closest to the beam intersection point in the experimental hall) are reserved for the installation of superconducting cavities. The klystron tunnels are sized for installation of one klystron and circulator per half cell; in fact, in the case of copper cavities each pair of half cells will have a common RF supply involving two klystrons. In the case of superconducting cavities, only one klystron per two half cells is necessary. The space thus freed is available for the installation of the refrigerator. It is almost indispensable to have one common refrigerator for all superconducting cavities located in the two half cells, i.e. for up to 16 four-cell cavities. This refrigerator would have to be installed in a tunnel section 16.6 m long, with a limitation in height given by the diameter of the klystron tunnel and by the the wave guides installed in it (see Fig.2 and Fig.3). Transport requirements (access to the tunnel through a vertical shaft 6 m long x 2 m wide) further limit the size of all components to be introduced into the tunnel.

The required cooling capacity of one refrigerator will be of the order of several kilowatts. The precise value depends not only on the accelerating field (square law), but also on the quality ('Q') factor of the cavity, which itself is field dependent. Fig.4 shows, for various zero-field Q factors and for a typical field dependence of Q on the accelerating field based on measurements, the dynamic heat load of 16 four-cell cavities in function of the field. If the zero-field Q value is 1*10**9, the dynamic heat load is about 4 kW at 5 MV/m. With a zero-field Q value of 3*10**9 (repeatedly measured at 350 MHz cavities), a field of 8 MV/m would be possible at roughly the same dynamic heat load (4.4 kW). Taking into account the need to cope with additional static heat loads and to have some safety margin for operational convenience under test conditions, it was concluded that a cooling capacity of the order of 6 kW would be desirable for the cooling of two half cells fully equipped with superconducting cavities.

The space available in the klystron tunnel, however, appeared not to be sufficient for the installation of this cooling capacity in form of refrigerators of conventional design. For reference, it may be stated that the BEBC helium refrigerator, the largest refrigerator presently in operation at CERN, has a capacity roughly equivalent to 3 kW at 4.5 K and measures 5.5 m in length (9 m required for dismantling), 2.1 m in diameter and 4.0 m in height (+ 0.8 m for servicing). Other known existing refrigerators at CERN and elsewhere are of similar compactness. Thus it appeared doubtful whether, for want of space, more than about 1 to 2 kW could be accomodated in the tunnel.

An optimum cooling temperature of about 4.5 K was tacitly assumed. This choice results not only from operational arguments (problems of air leakage into components operated at subatmospheric pressure), but also from compactness considerations (large cross section required for heat exchanger passages at low pressure).

In order to identify the main factors governing the compactness of a refrigerator and to determine which conceptual changes, new component developments and concessions on traditional requirements could lead to smaller size, CERN has approached three firms specialized in the construction of low temperature refrigerators (L'Air Liquide/France, Linde/Germany and Sulzer/Switzerland) to study possibilities for installation of maximum cooling power in the given space. These studies are presently under way.

Although it is certainly premature to draw conclusions, some preliminary statements can be made.

(a) The size of the refrigerator is determined by the size and number of the heat exchangers and by the complexity of the plant (internal piping, valves etc.).

(b) Some gain on the size of the heat exchangers may be possible by careful analysis of entropy production, but generally traditional heat exchanger specifications, as regards temperature differentials, seem to be close to optimum. (An increase of the temperature differential across a heat exchanger has the ambivalent consequence of directly reducing the heat exchanger size because less heat exchange surface is required and of indirectly increasing it because a higher gas flow is needed to compensate for the reduced plant efficiency; in optimum design the two effects are balanced.)

(c) All firms assumed that a cycle with two expansion turbines for precooling and a third one instead of the classical Joule-Thomson valve would be optimal; a plant with more than three turbines might be somewhat more efficient, but would be less compact due to increased complexity.

(d) All firms considered that separate routing of low pressure gas from the load and low pressure gas from the turbines would not lead to a more compact plant because of its increased complexity.

(e) Considerable gain in compactness is possible by careful layout of pipework, valves and auxiliary components and by special design of the heat exchanger headers.

(f) Drawbacks of compact design are reduced possibilities for subsequent adaptation or further development of a tailor-made plant and possible complication of assembly, maintenance and repair work, hence higher requirements on testing prior to assembly and on reliability of certain components. These drawbacks are the reason why compactness is not usually pushed to extremes in conventional refrigerators.

(g) Exploiting all space saving possibilities, one might arrive at a cooling capacity of 3 to 5 kW installed in a horizontal cold box 5.6 m long, 1.8 m wide and not much higher than 2 m, i.e. a box that will pass through the access shaft in one piece in normal horizontal orientation. For higher cooling capacities either a special cold box design suitable for vertical transport or a double-box layout for the plant or a cold box finally assembled in the tunnel could be considered; in this case, it should even be possible to exceed 6 kW at 4.5 K.

(h) The cooling capacity depends strongly on the cross section of the cold box. A reduction of the cold box width from 1.8 m to 1.5 m (i.e. by 17%) might reduce the cooling capacity to half of its value or less.

3. Cryostats

Cryostats for the superconducting cavities are being developed along two complementary lines.

One cryostat type, with an all-welded helium vessel, gives top priority to extreme structural reliability. The other one, with a bolted helium vessel and a rather non-conformist vacuum tank, is optimized for easy access to the cold components of the system in view of progressive adjustments and modifications; it allows for partial dismantling and reassembly in situ.

Presumably the advantages of the welded cryostat will become dominant in the final phase of the cavity programme, when the cavity and its ancillary cold equipment have reached their definite state and the need for adjustment and modifications disappears, while the bolted cryostat may have decisive advantages in initial development phases.

Fig.5, showing a cryostat developed by W.K.Erdt, with a flanged vacuum tank and an all-welded helium vessel, is an enlarged view of half of one of the twin cryostats appearing at the bottom of Fig.1. The inserts indicate how the disassembly problem is solved by providing extended sleeves for welding, which can be cut if necessary by means of a special tin-opener type tool. A welded joint can thus be remade several (about ten) times if necessary.

Fig.6 shows an experimental cryostat presently under construction, designed along these principles.

Fig.7 and Fig.8 are exploded views of the vacuum and the helium tank of a bolted cryostat developed by R.G.Stierlin. The vacuum tank has a removable side wall consisting of a 1.5 mm thick stainless steel skin supported by reinforcement shells and ribs bolted to the tank frame and bottom bar. The main seal is a rubber gasket along the edge of the sealing skin. The large aperture at the top is designed for an experimental programme of maximum flexibility. The bolted helium tank is shown in Fig.8; sealing is achieved by means of lead which resists to the high temperatures to which the tank will be subjected during thermal treatment of the cavity. Aluminium is largely used instead of stainless steel both at the vacuum and the helium tank, and the design avoids large machined flanges for reasons of cost saving. A photograph of the bolted cryostat while being assembled is shown in Fig.9.

Figure captions

Fig.1: Topology of the LEP RF and klystron tunnels. Copper cavities are installed in the four half-cells of the machine lattice between quadrupole magnets Qs7 and Qs11. Installation of superconducting cavities is envisaged in the two half-cells between quadrupoles Qs4 and Qs6. At the bottom of the figure, a longitudinal section shows one half-cell of the RF tunnel, equipped with eight superconducting four-cell cavities. The cavities are installed in four twin cryostats as described in section 3.

Fig.2: View into a LEP klystron gallery. A strip of 16.6 m length is available for the installation of the refrigerator cold box and ancillary equipment. The lines extending to the left are wave-guides feeding the superconducting cavities in the RF tunnel, located about 9 meters left of the klystron tunnel.

Fig.3: Cross section through klystron tunnel showing space available for refrigerator cold box.

Fig.4: Dynamic heat load of 16 superconducting four-cell cavities (i.e. two fully equipped half-cells of the lattice) in function of accelerating field and quality factor Q. Q is field-dependent; the graphs are based on typical measurements.

Fig.5: Design of a cryostat with all-welded helium vessel (right half of one of the twin cryostats shown at the bottom of Fig.2).

Fig.6: Horizontal test cryostat presently under construction, using all-welded design, as indicated in Fig.5, for the helium vessel.

Fig.7: Vacuum tank for cryostat of bolted design (schematic).

Fig.8: Helium vessel for cryostat of bolted design, to be installed in the vacuum tank shown in Fig.7 (schematic).

Fig.9: Photograph of bolted cryostat components (helium tank at the left, vacuum tank at the right).

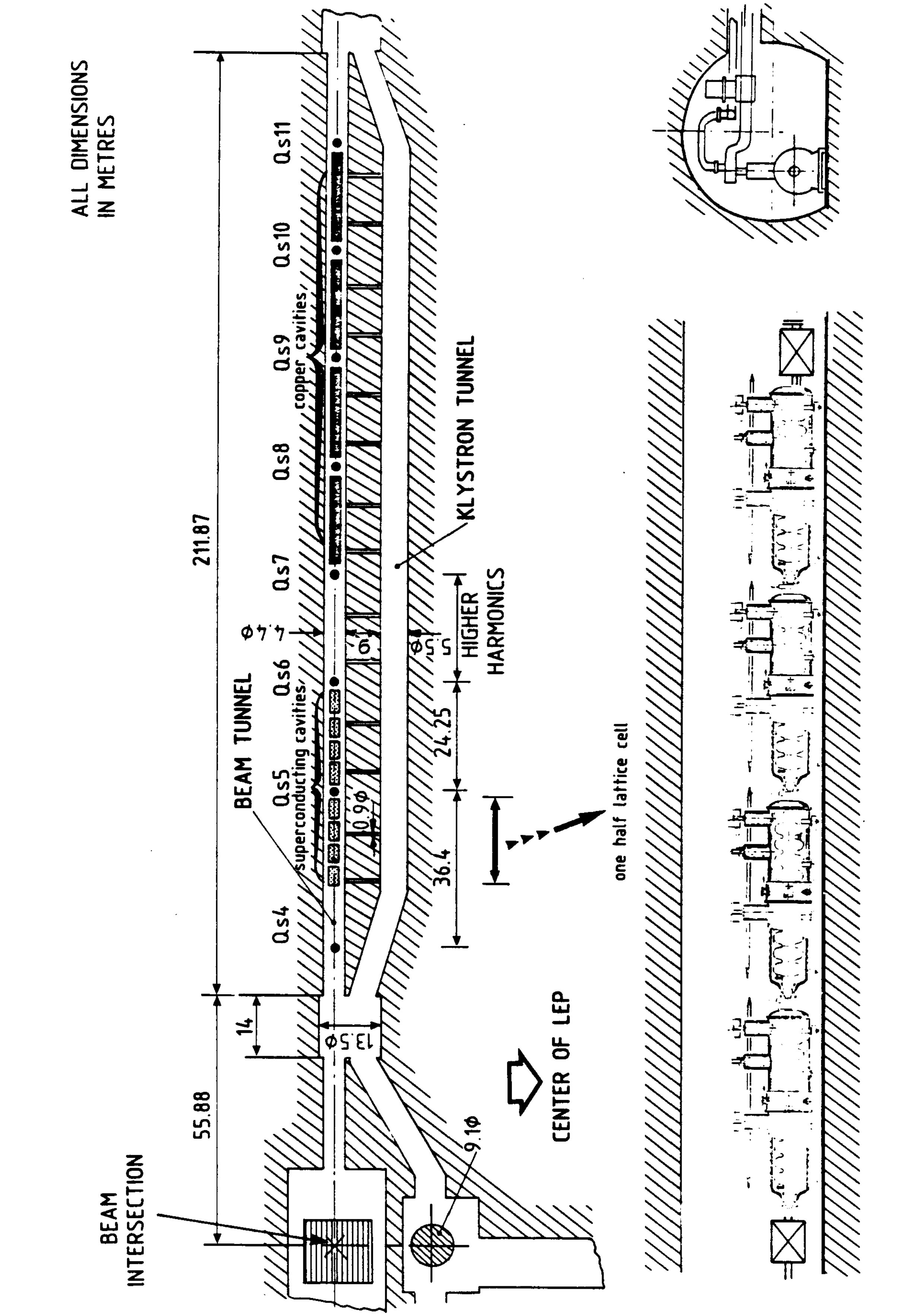

ALL DIMENSIONS
IN METRES
211.87
Qs4
Qs5
Qs6
Qs7
Qs8
Qs9
Qs10
Qs11
superconducting cavities
copper cavities
BEAM TUNNEL
KLYSTRON TUNNEL
HIGHER
HARMONICS
36.4
24.25
14
55.88
13.5Φ
9.1Φ
CENTER OF LEP
BEAM
INTERSECTION
one half lattice cell

Fig. 1

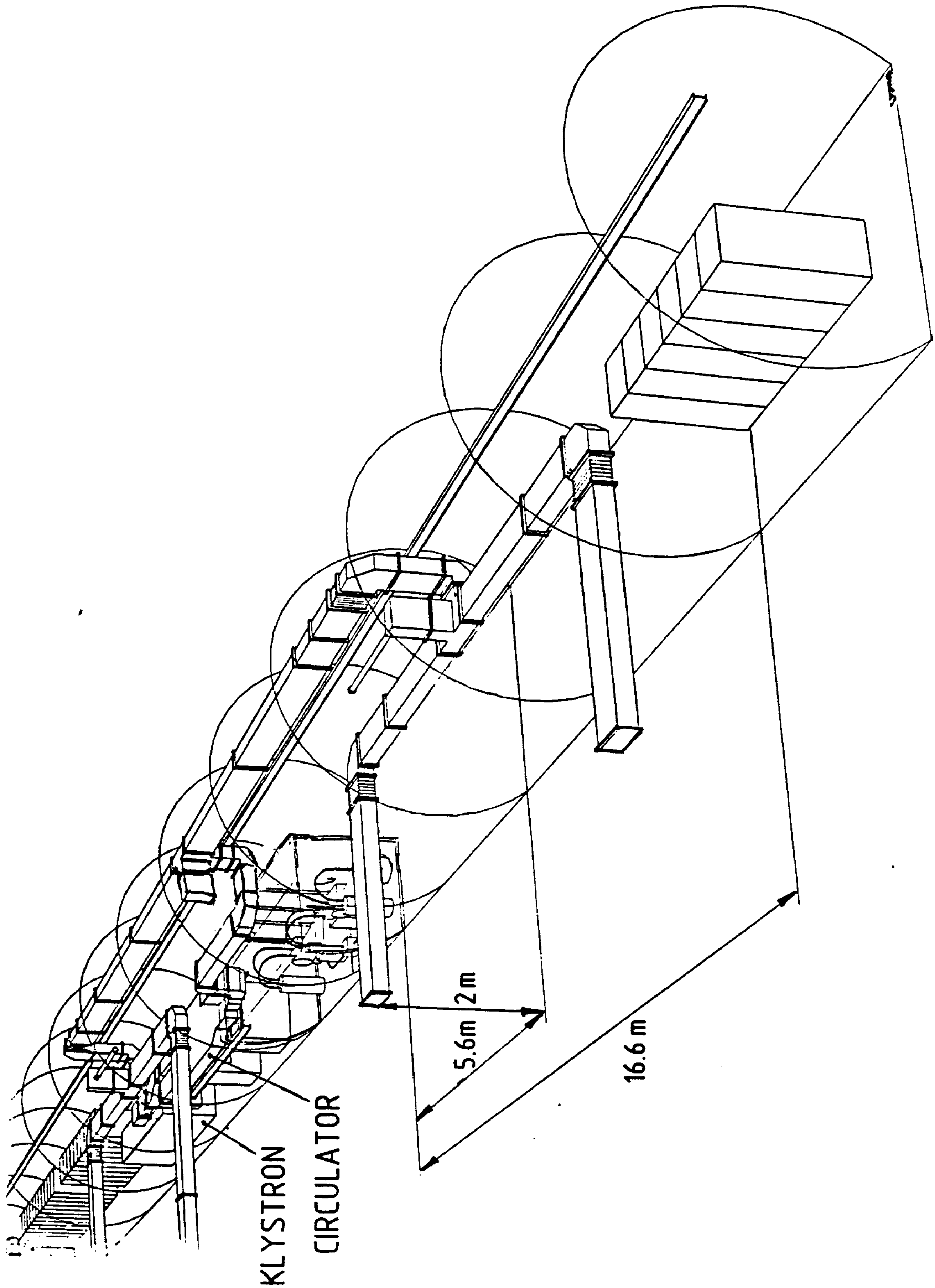


Fig. 2

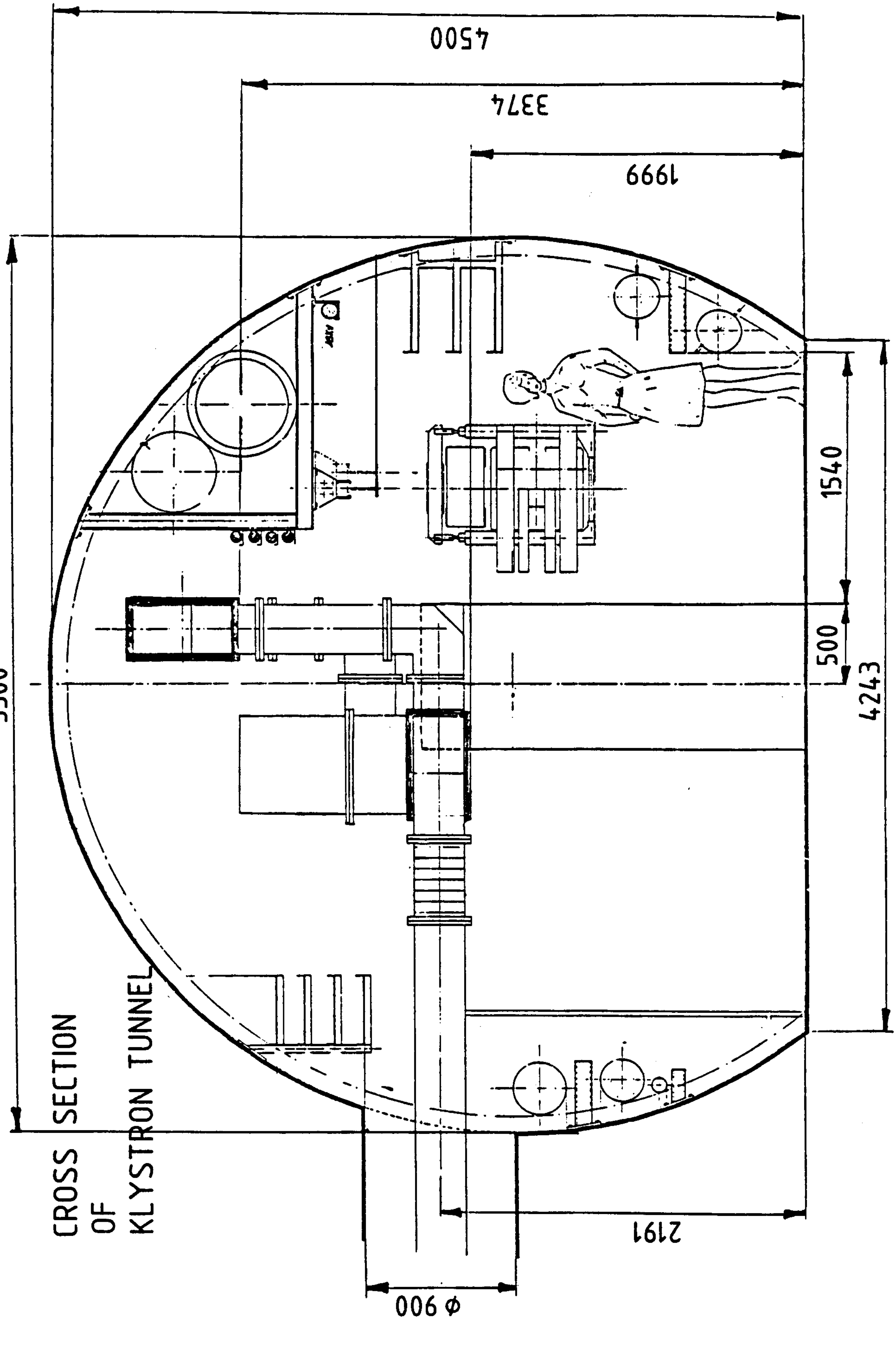

CROSS SECTION
OF
KLYSTRON TUNNEL
4500
3374
1999
5500
1540
500
4243
2191
φ 900

Fig. 3

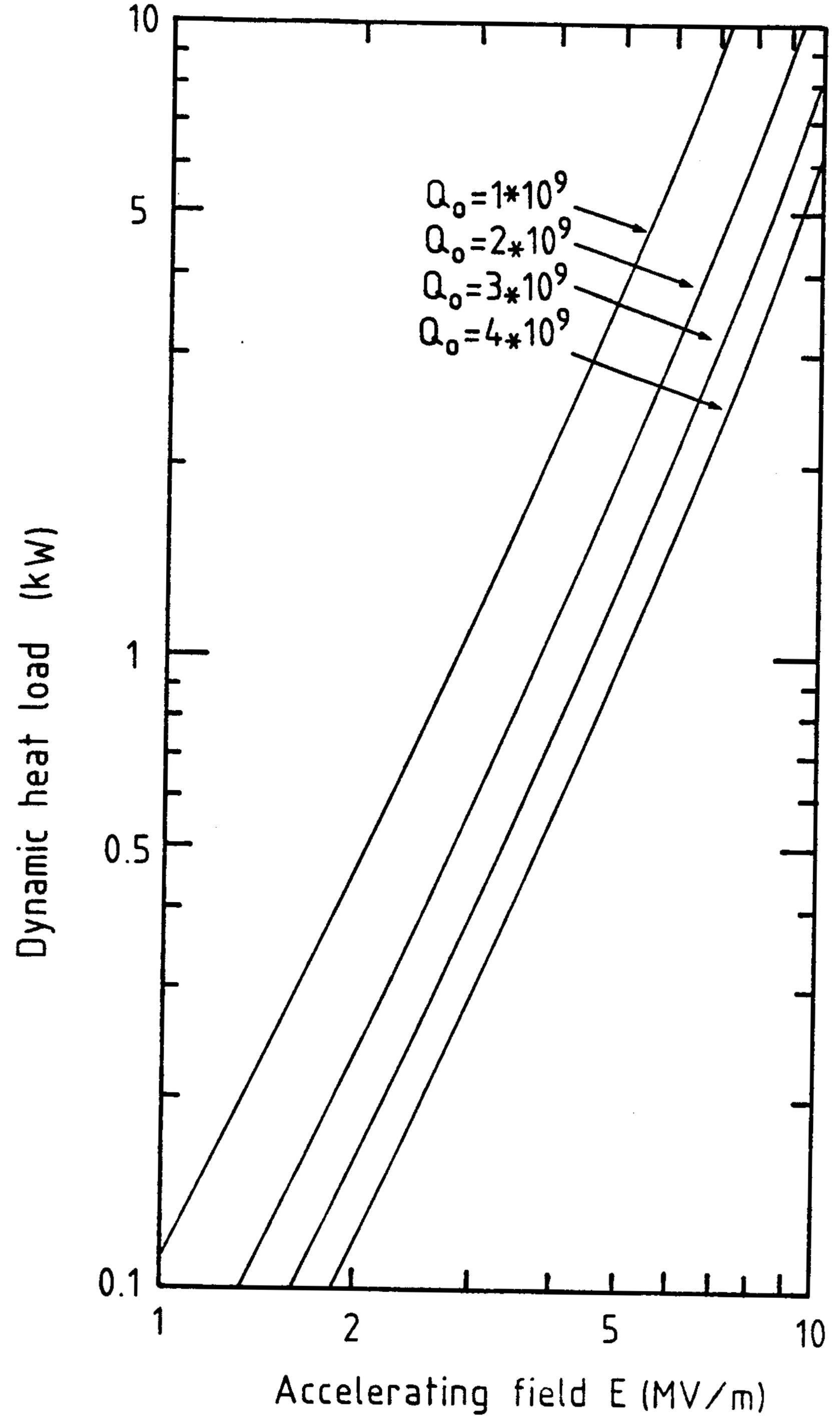

10
5
1
0.5
0.1
1
2
5
10
Dynamic heat load (kW)
Accelerating field E (MV/m)
Q0=1*10^9
Q0=2*10^9
Q0=3*10^9
Q0=4*10^9

Fig. 4

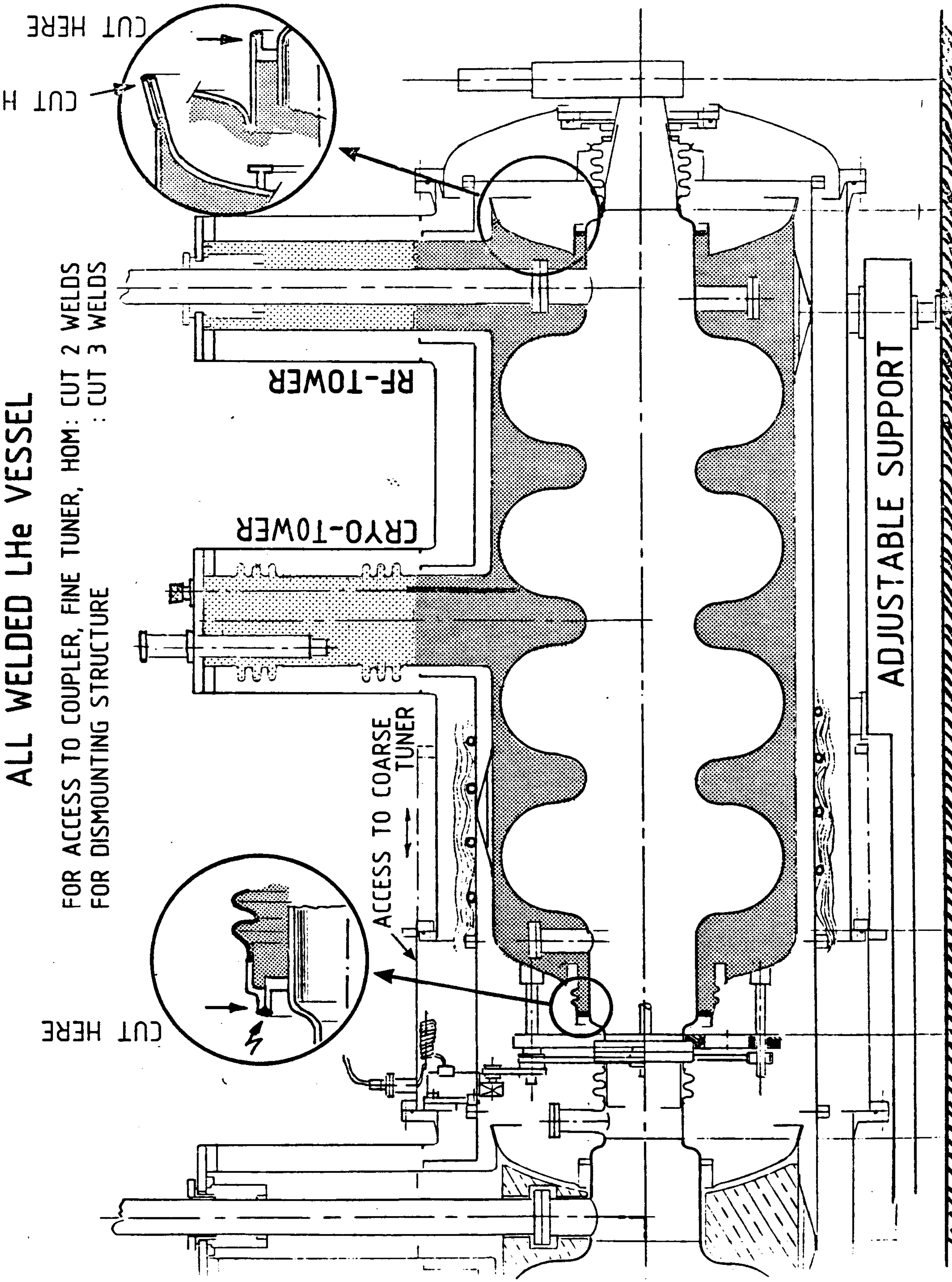
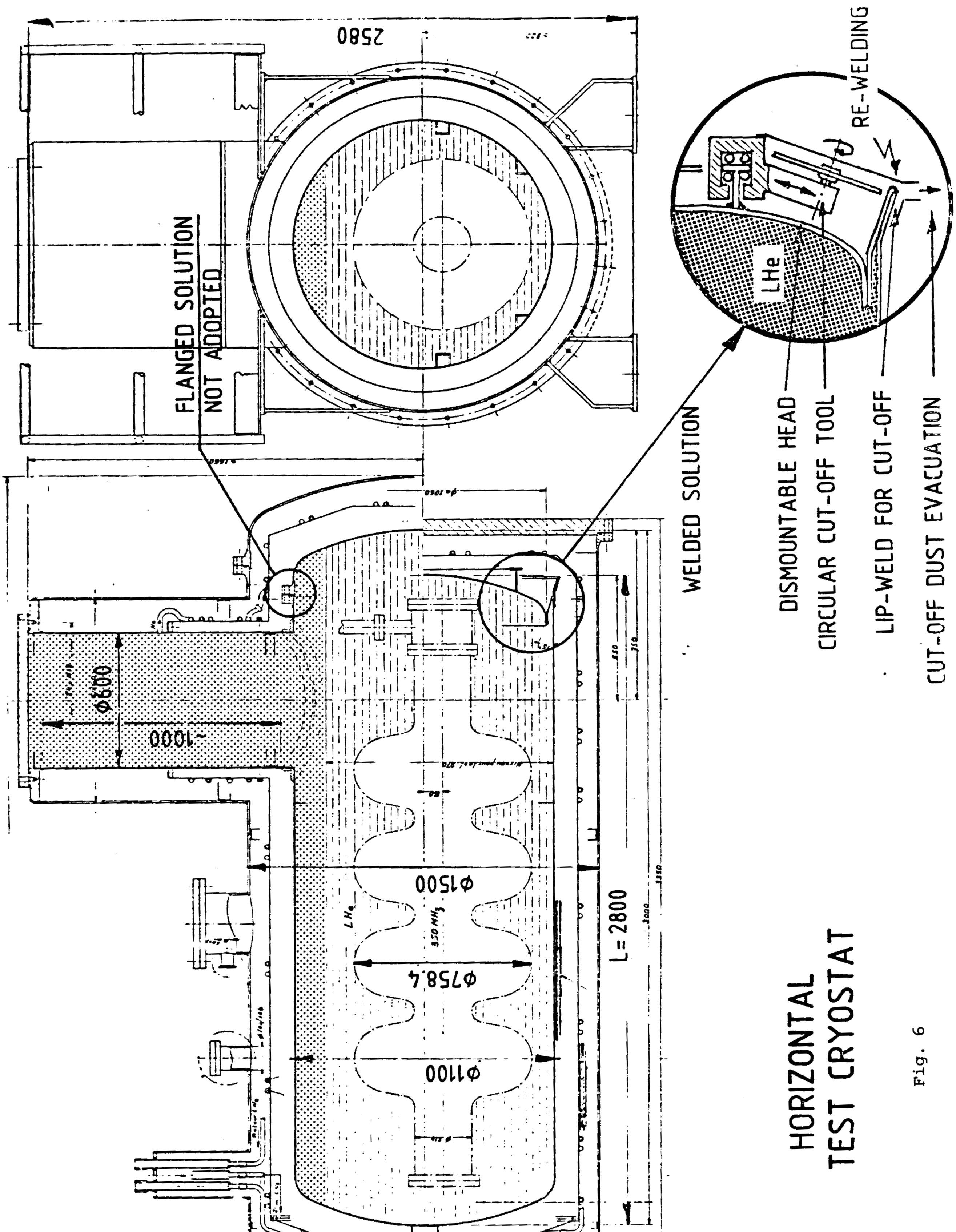

ALL WELDED LHe VESSEL
FOR ACCESS TO COUPLER, FINE TUNER, HOM: CUT 2 WELDS
FOR DISMOUNTING STRUCTURE : CUT 3 WELDS
CUT HERE
CUT HERE
CUT HERE
RF-TOWER
CRYO-TOWER
ACCESS TO COARSE TUNER
ADJUSTABLE SUPPORT

Fig. 5



HORIZONTAL TEST CRYOSTAT

Fig. 6

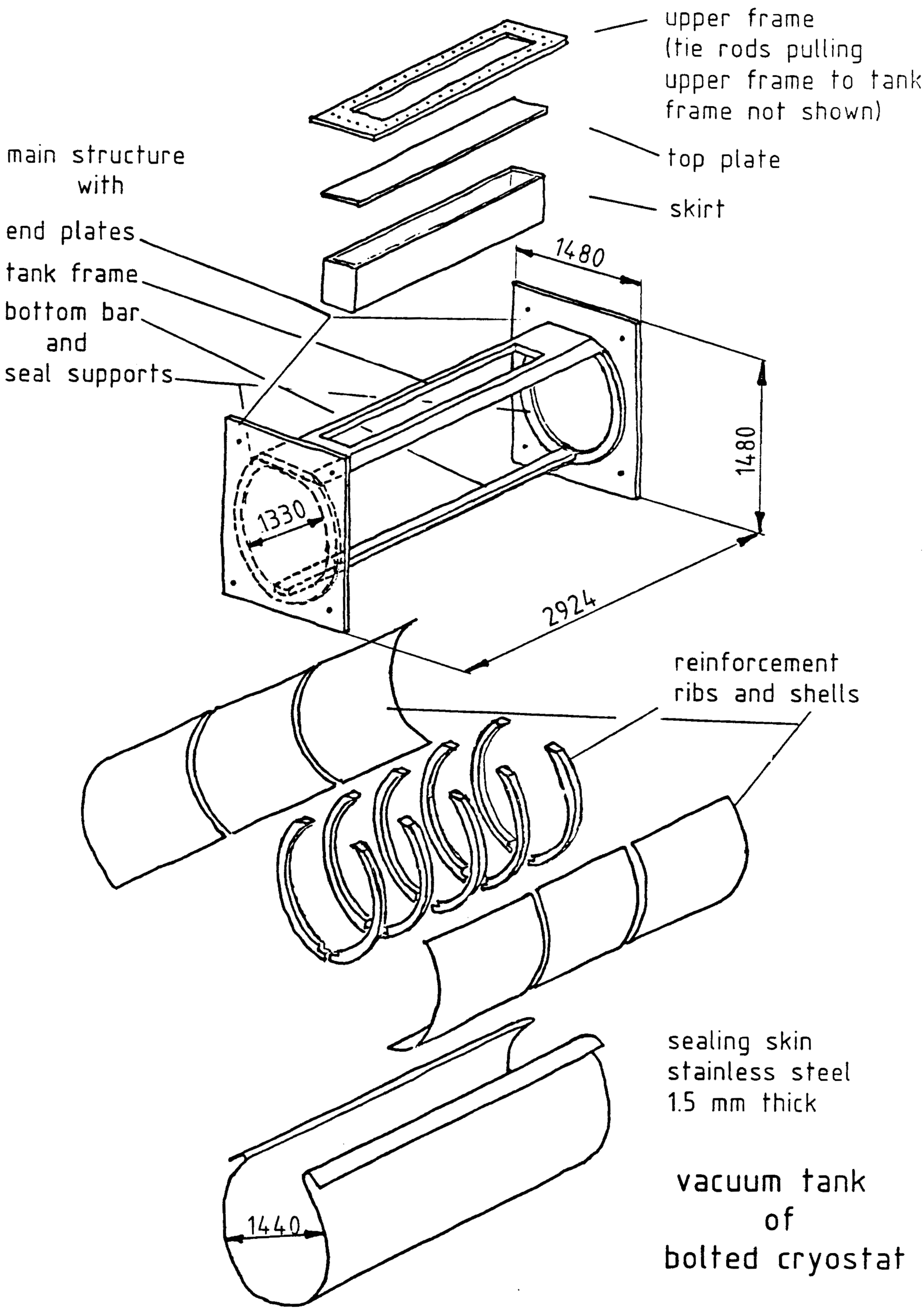

upper frame
(tie rods pulling
upper frame to tank
frame not shown)
top plate
skirt
main structure
with
end plates
tank frame
bottom bar
and
seal supports
1480
1480
1330
2924
reinforcement
ribs and shells
sealing skin
stainless steel
1.5 mm thick
1440
vacuum tank
of
bolted cryostat

Fig. 7

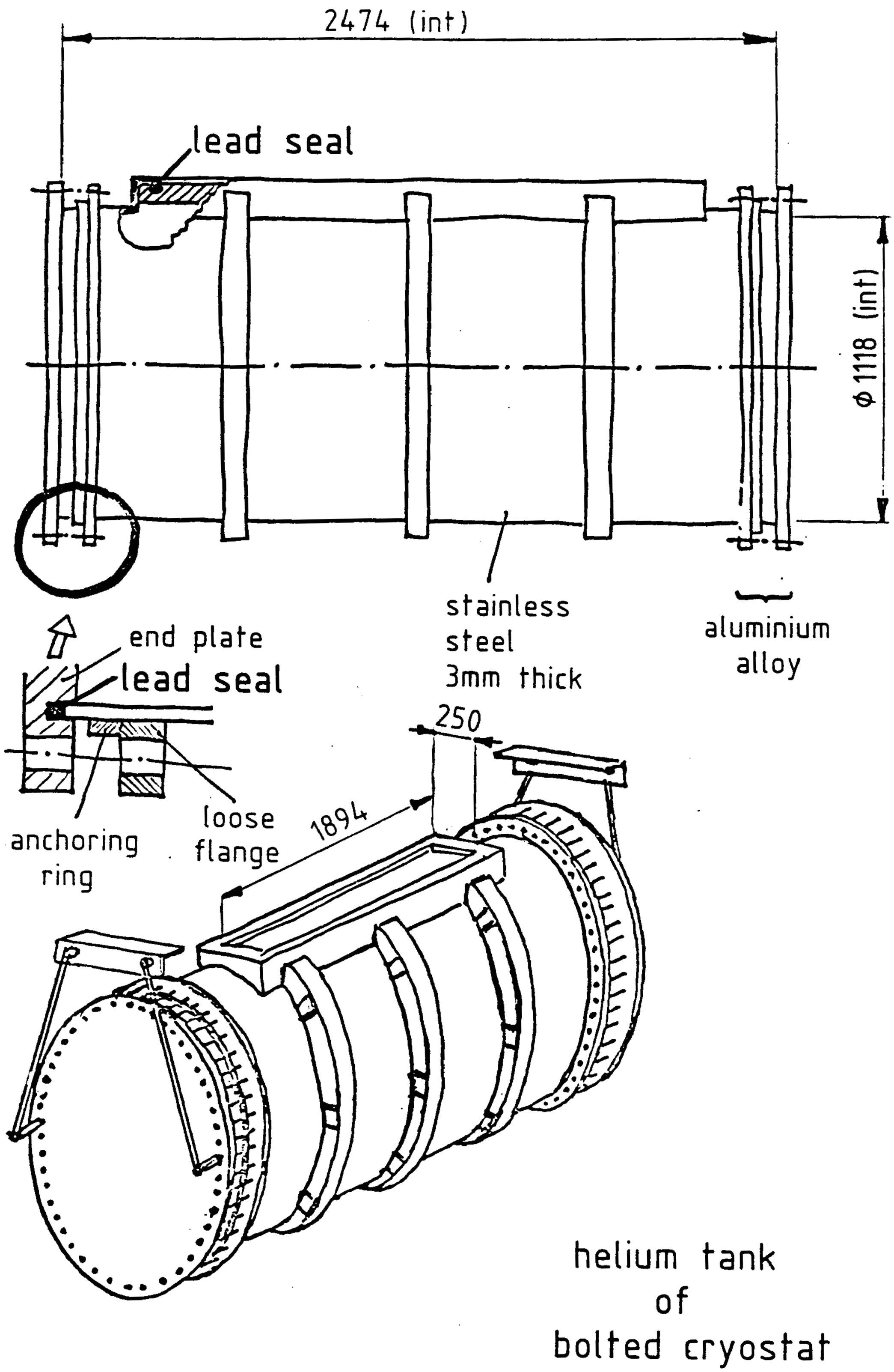

2474 (int)
lead seal
φ 1118 (int)
stainless
steel
3mm thick
aluminium
alloy
end plate
lead seal
anchoring
ring
loose
flange
250
1894
helium tank
of
bolted cryostat

Fig. 8

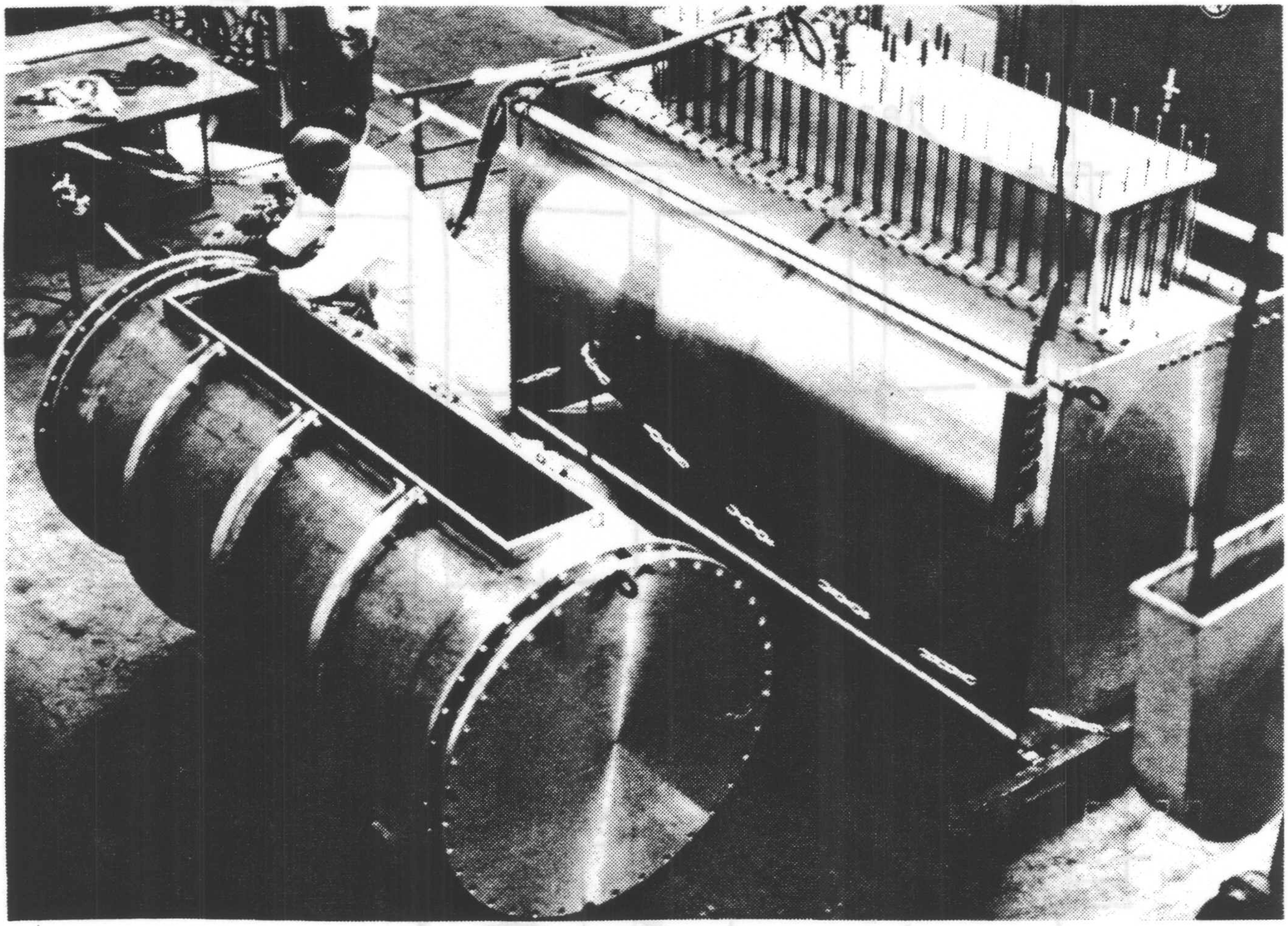


Fig. 9