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PRELIMINARY STUDY OF A SUPERFLUID HELIUM CRYOGENIC SYSTEM FOR THE

LARGE HADRON COLLIDER

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1. INTRODUCTION

The installation of a Large Hadron Collider (LHC) in the LEP tunnel is being considered at present.

With a given average diameter of the collider, the only possibility for increasing the energy of the accelerated hadrons is given by the use of superconducting dipoles producing high magnetic field. To obtain field in the range of 8 to 10 T, either Nb_3Sn at 4.5 K or Nb-Ti at lower temperature (typically 1.8 K) can be used. In figure 1 short-sample characteristics of the two types of superconductors are plotted; it is shown that in the range of 10 to 11 T Nb-Ti at 1.8 K can carry a current density somewhat higher than Nb_3Sn available at present. The high current capacity of Nb-Ti at 1.8 K combined with the peculiar properties of superfluid helium (in particular its very high thermal conductivity) makes clear the interest of studying a magnet system operated at 1.8 K.

Whilst it is believed that the manufacturing of magnets using Nb-Ti is somewhat simpler than in the case of Nb_3Sn, the feasibility of a cryogenic system for the LHC at 1.8 K needs to be assessed. This is precisely the purpose of this preliminary study.

In this paper we will assume the same constraints and the same general boundary conditions (e.g. tunnel size, distance between access pits, etc.) as used in the 4.5 K study (see ref. [1]).

We will point out the main differences between the 1.8 K and 4.5 K cryogenic systems and we will try to give the first elements to make possible a comparative evaluation of the two solutions.

2. HEAT LOADS IN STEADY OPERATION

The preliminary study of a 4.5 K cryogenic system for the Large Hadron Collider [1] assessed the large size of the required refrigeration and, consequently, the high electrical power consumption. In these conditions, to be acceptable, a superfluid helium cryogenic system operating at 1.8 K should have only marginally higher power requirements. For thermodynamic reasons refrigeration at 1.8 K is more expensive than at 4.5 K, as concerns grid power consumption (see paragraph 4). It therefore appears essential to keep to a minimum the heat load at 1.8 K by (a) intercepting most of the heat at higher temperatures, and (b) limiting power dissipation in the superfluid.

To evaluate the heat input at 1.8 K we will try to make an analysis of the various sources of heat entering the magnet cryostat.

The heat sources can be subdivided into three categories.

As in any cryogenic system, the first heat source is the ambient temperature environment. Standard techniques of cryogenic engineering will be employed to limit heat inleaks, e.g. insulation vacuum better than 10^{-5} mbar, radiation shield and heat intercepts cooled at intermediate temperatures, use of multilayer superinsulation, choice of low thermal conductivity materials for structural supports (e.g. fibreglass-epoxy composites) and their thermal bridging to heat intercepts.

A second source of heat is Joule dissipation in resistive sections of the electrical circuits, e.g. current leads and non-superconducting joints in the magnet windings. The former can be kept low by proper design, the latter are unavoidable, and can only be (partially) reduced by developing techniques for obtaining reproducibly ultra-low resistive joints. Incidentally, it can be noted that, in general, the ohmic resistance of joints of Nb-Ti composite is lower than in the case of Nb_3Sn. In this class of heat sources one should also count power dissipation in instrumentation sensors equipping the cryostats, as well as eddy current dissipation in superconductors, matrix and magnet structure induced by ramping current during acceleration. The slow ramping rate (e.g. maximum field reached in about 10 minutes) makes these heat sources negligible.

The third source of heat in the cryogenic environment is the circulating hadron beams in the LHC, which produce synchrotron radiation in the UV range (critical energy of the spectrum is 71 eV at peak beam energy), induce electrical image currents in the conducting walls of the beam channel and lose energetic particles by interactions with the residual gas or with the beams themselves. The first two processes have been estimated to dissipate up to a maximum of 0.3 W m^{-1} [1,2], which can easily be intercepted by a metallic shield located inside the magnet aperture, at the cost of a slight reduction in useful aperture. Possible technical designs for such a shield appear in figure 2. As for the effect of particle losses, first estimates based on crude assumptions show that very little power would be deposited in the cryostats.

The detailed breakdown of steady operation heat loads (without contingency factor) appears in Table 1, and calls for the following comments:

1. It has been assumed to have three temperature levels in the system, namely 90 K, 4.5 K and 1.8 K. The 4.5 K temperature, which may not correspond to the thermodynamic optimum, has been chosen for practical reasons, as will be explained in paragraph 5.

2. The heat load at 1.8 K can be kept down to about 0.2 W m^{-1}, a value low enough not to penalize the 1.8 K solution with respect to 4.5 K cryogenics.

3. The heat loads at 90 K and 4.5 K are comparable to those of the conventional cryogenic system (reference 1).

4. A more refined heat load analysis can only be made at the component design stage, and will be quite sensitive to constructional details. Furthermore, additional work should be done in order to assess the externally imposed heat loads, in particular the effects of the circulating hadron beams which, in the present design, justify the presence of the beam shield.

3. POSSIBLE REFRIGERATION SCHEMES

3.1 General

The refrigeration scheme shall provide means:

(a) to produce the required cooling power

(b) to distribute the cooling power required by the magnets in steady operation

(c) to cool down the magnets from room temperature to the final operation conditions

(d) to recool rapidly a short string of magnets after a quench.

The cryogenic system at 1.8 K should comply with the same basic principles applied in the 4.5 K option, i.e. flow of two-phase fluid over long distances should be avoided, the magnet cyrostats should not be at sub-atmospheric pressure and some cooling redundancy should be provided.

3.2 Steady Operation at 1.8 K

The properties of superfluid helium can be used to cool elements located at some distance from the cold source simply by heat conduction through a static column of helium.

Basically the refrigeration by conduction is schematized in figure 3. The cold sources C are connected to the magnets through pipes containing static superfluid helium.

Since the thermal conduction of superfluid helium is large but finite, the system can be used in practice only to cool magnet strings of a few ten-metre lengths, i.e. half or at the most, one machine cell (79 m). E.g. assuming a power input of 0.2 W m^{-1}, a cold source temperature of 1.8 K and a string length of 80 m, a column diameter of at least 60 mm is required to maintain the temperature of the warmest point of the string below 2 K.

The limitations of the heat transport by conduction [3] between 2.0 K and 1.8 K are illustrated in fig. 4 where, for several values of heat input per metre length, the required diameter of the static superfluid helium column is given as a function of the magnet string length.

The cold sources indicated in figure 3 can be either distributed small refrigerators or heat exchangers transferring to the short strings of magnets a fraction of the cooling power produced by larger plants concentrated at the eight access points.

Magnetic refrigerators (which, however, up to now have been developed only as laboratory prototypes) could be used in the first case. The corresponding scheme is shown in fig. 5.

Single- phase cold helium (e.g. 4.5 K and 3 bar) produced by octant refrigerators installed at the access points, is distributed along the machine ring and expanded through valves LCV into the pots P which are filled with boiling helium at 4.5 K. The vapour is returned through a second line. Magnetic refrigerators located in the pots provide the cooling power at 1.8 K using the 4.5 K helium as warm source.

The case in which concentrated refrigerators are used is illustrated in the scheme of fig. 6. Again, single-phase subcooled liquid helium is distributed along the machine ring (line β) and expanded in the pots P which are filled with boiling helium at 1.8 K at the corresponding pressure of about 16 mbar. The cold pumping line (α) is connected to cold centrifugal pumps in the cold boxes of the octant refrigerators. The heat exchangers in the pots transmit the cooling power at 1.8 K to the magnet cryostats which are filled with superfluid helium at 1 bar pressure.

3.3 Initial cooling down

The initial cooling down of the machine, from room temperature to final operation conditions, requires the addition of extra valves and pipes to the schemes of figs. 5 and 6. The modified schemes are shown in figs. 7a and 7b. At the beginning of the cooling down, valves LCV are closed and a stream of progressively cold helium is introduced in the magnet through valves V and returned through valve SRV. Valves SRV are non-return valves which are also used, in normal operation, as discharge valves in case of magnet quench. When the magnet has reached the temperature of 4.5 K valves V are closed, valves LCV are opened and the cooling down to 1.8 K can be initiated. The cooling down time from room temperature to 4.5 K will be at parity of other conditions exactly the same as in the case already discussed in ref. [1], i.e. approximately 400 h.

The cooling down time from 4.5 to 1.8 K will essentially depend on the installed refrigeration power and on the amount of helium contained in the magnet cryostat and in the connecting piping. The mass of the magnet is of secondary importance and it can be shown that very little or no time could be gained by a solution where the magnet iron yoke is kept at a temperature higher than the coil. Assuming a constant cooling power of 0.5 W m^{-1} in the range 4.5 to 1.8 K and a helium content of 5 l m^{-1} (including piping), the cooling down time from 4.5 to 1.8 will be about 6 hours.

3.4 Re-cooling after a magnet quench

The time required for the initial cool-down is not critical since it is assumed that the machine will normally be kept cold: warming-up and recooling down of the entire machine should occur only during major shutdowns.

It is much more important to minimize the time required to bring the accelerator back into operating condition after a quench (and subsequent warming up) of one (or of a small number) of machine magnets. It is expected that these quenches can occur frequently. From the point of view of the machine operation a recovery time, after a quench, of the order of one hour

would be desirable. From this point of view the scheme of figs. 6 and 7b with concentrated refrigerators is preferable to the scheme of figs. 5 and 7a. In fact, in both cases each refrigerator will necessarily have a cooling power exceeding the cooling power required in steady normal operation. However, in the case of concentrated refrigerator (figs. 6 and 7b) it will be possible to shift all the excess power available in a half octant to the quenched magnet(s) and, consequently, reduce the re-cooling down time. In the case of distributed refrigerators (figs. 5 and 7a) the power available to recool one quenched magnet is smaller and it is limited to the excess power of a single distributed refrigerator.

4. HE II REFRIGERATORS

The He II bath contained in the magnet cryostats must be kept at the correct temperature by means of cold sources thermally coupled to the bath. At present two types of cold sources are available.

In the first and most classical type the refrigerating power is obtained by pumping over a bath of boiling superfluid liquid helium which is maintained at a pressure (in the range between 10 to 20 mbar) corresponding to the desired temperature.

In the second type of cold source the refrigeration power is obtained through a magnetisation-demagnetisation cycle of an appropriate material. The magnetic refrigerators are at present under development and have proven to be effective, at least, as laboratory prototypes.

4.1 Gas cycle refrigerators

The scheme of fig. 8a shows the most classical and oldest type of pumped refrigerator.

The liquid helium at 4.5 K is passed through a heat exchanger HE and then expanded through a valve to a lower pressure corresponding to the desired

temperature. The low-pressure cold vapour is returned to the compressor input through the heat exchanger HE, the cold box heat exchangers and a pump P_w. This scheme has been adopted, e.g. in the 1.8 K refrigerators installed in the past at Karlsruhe [4,5], Stanford [6] and CERN [7,8]. The disadvantages of this scheme are the very low pressure heat exchangers, which are difficult to design and to manufacture, and the pump P_w (usually a multi-stage Roots pump) which has a very large size, further increased by the non-negligible pressure drop in the heat exchangers.

In a more modern plant for the refrigeration of the fusion Tokamak Tore Supra [9] the scheme has been modified (see fig. 8b) by the addition of a cold pump P_c. This cold pump is a two-stage centrifugal compressor developed by industry with the purpose of raising the pressure of the vapour returning to the cold box from 13 to 80 mbar. In this way the design and construction of the heat exchangers becomes a much more conventional problem. Furthermore, for pressure above 80 mbar it is possible to use, for the warm pump P_W, oil ring type pumps which are known for their reliability.

Pumped refrigerators appear suitable for producing power at low temperatures in the range of 100 to 1000 watt.

The measured efficiency of the 1.8 and 4.5 K refrigerators can be judged from Table II where low temperature refrigeration and the corresponding required electrical power are listed for a number of existing refrigerators. The table allows the calculation of the electrical powers $P_{1.8}$ and $P_{4.5}$ required for one watt of refrigeration respectively at 1.8 and 4.5 K. The ratio $P_{1.8}/P_{4.5}$ is in the range 1.4 to 2.0, lower than the ratio of the temperatures 4.5/1.8 as in the case of an ideal Carnot's machine. This simply reveals that, in practice, the efficiency (relative to the Carnot's cycle) of a 1.8 K refrigerator is somewhat higher than in the corresponding 4.5 K plant. It is worth noting that Table II refers to small or medium size plants and better performances can be anticipated for larger and more modern installations.

4.2 Magnetic cycle refrigerators

The magnetic refrigerators make use of the entropy variation of some materials as a function of the magnetic field. Today, high magnetic fields can be easily produced and materials are available showing strong entropy dependence on magnetic field in the range 1 to 10 K. For example, in fig. 9 the entropy diagram for a $Gd_3Ga_5O_{12}$ crystal is given. The Carnot's cycle (rectangle ABCD) shows how a refrigerator using these materials works.

Starting from the lowest temperature (point A) an adiabatic magnetisation (AB) is followed by an isothermal magnetisation (BC) where heat is released to the warm source. Then, an adiabatic demagnetisation (CD) is followed by the isothermal BA where heat is extracted from the cold source. In a prototype machine [10] using 9 cm^3 of gadolinium gallium garnet and a 3 T maximum field a refrigeration power exceeding 1 W has been produced in the range 1.8 to 2 K with an efficiency between 50% and 70% of the Carnot's cycle at a cycle frequency of about 1 Hz.

Magnetic refrigerators seem to be suitable for units producing cooling power of the order of 10 W.

5. REFERENCE DESIGN

In this paragraph a so-called reference design of a superfluid helium refrigeration system for the Large Hadron Collider is presented. The words "reference design" should not be understood as "optimised solution" but rather as a possible scheme which has been studied in some detail and to which the characteristics and performance figures quoted below refer.

The boundary conditions used to establish this scheme are identical to those of reference [1]. In particular, the size and general layout of the tunnel, as well as the structure and periodicity of the accelerator, are conserved. Moreover, the dipole magnets are assumed to be identical in design and size to those of [1] (two-in-one, cold iron structure). The scheme presented here has been designed to provide normal operation of the magnets and to cope with cool-down, warm-up and quench recovery. It also features

some redundancy, in the form of over-capacity and the possibility of distributing it where needed in case of failure or unavailability of some components.

5.1 System Description

The basic scheme of the "reference design" is the one shown on figs. 6 and 7b, i.e. the solution with concentrated refrigerators. The elementary block of the refrigeration distribution system, which corresponds to a half-cell of the accelerator lattice (39.5 m) is shown in more detail in figure 10. The magnet coils are immersed in static superfluid helium at temperatures of 1.8 to 2.0 K and atmospheric pressure, through which heat is transported by conduction to local refrigeration stations, spaced by 39.5 m. Each refrigeration station consists of a cryostat where subcooled liquid helium at 2.2 K, fed from line β, is expanded down to 16 mbar, i.e. the saturation pressure at 1.8 K. The heat conducted by the static pressurized superfluid helium is absorbed in the refrigeration station by vapourisation of saturated superfluid helium, the level of which is maintained constant by expansion valve LCV. The cold helium vapour produced by the expansion process and the refrigeration load is returned to the octant refrigerator via the low-pressure line α. Thirty-five such local refrigeration stations are required per half-octant.

Monophase helium at 4.5 K, 3 bar, tapped from line δ through valve TCV, is expanded through the cooling channels of the inner radiation shields installed in the beam pipes (see figure 2) to intercept synchrotron radiation and other beam-induced heating. The same helium flow intercepts the heat conducted along the magnet supports before returning to the octant refrigerator via line γ. Line γ, which is maintained cold during operation of the system, is also used to recover helium discharged from the magnet cryostats in case of quench, through the relief valves SRV.

Quench propagation from one magnet string (3 magnets) to the adjacent ones is very difficult because the 1.8 K cooling systems of magnet strings are not hydraulically connected and thermally buffered by the local refrigeration station.

In the refrigeration distribution scheme three temperature levels are used, namely, 1.8, 4.5 and 90 K. The choice of the 4.5 K temperature level to cool the beam shield and the heat intercepts of the cryostat does not correspond to the thermodynamical optimum. From this point of view a higher temperature (in the range of 10 to 20 K) would be preferable. However, the 4.5 K level has been chosen because (a) this low temperature is very useful for the initial cooling down, or the recooling after a quench, before the 1.8K refrigeration is started (b) lenses and correction magnet could probably be operated at 4.5 K.

Cool-down and warm-up of a magnet string are achieved by forced circulation of gaseous helium, tapped from line δ through valve CDV and returned to the octant refrigerator through valves SRV and line γ.

The standard transverse cross-section of a two-in-one dipole cryostat is shown in figure 11. The static pressurized superfluid helium is contained in the two pipes enclosing the magnet coils. These pipes, which contain about 5 l m^{-1} of helium, closely fit the magnet yoke and mechanical structure, which is therefore also maintained at 1.8 K. All lines α, β, γ and δ are enclosed in the cryostat vacuum vessel, and thermally shielded from the ambient temperature wall by a liquid-nitrogen cooled superinsulated screen. For the sake of simplicity and limited transverse space occupancy, there is no intermediate temperature structure between the 90 K screen and the 1.8 K assembly. Only superinsulation is used there to reduce radiative heat inleak to the magnet. However, the magnet support columns, made of glass-fibre reinforced epoxy are thermally bridged to the 4.5 K level.

In a first approximation figure 11 shows that overall transverse dimensions of the LHC cryostats are compatible with the space available in the LEP tunnel [1].

The general refrigeration flow scheme in one octant is schematized in figure 12: the octant refrigerator normally serves the two adjacent half-octants. It could be sized for 50% overcapacity providing redundancy in case of failure of an adjacent octant refrigerator, the load of which could then be shifted to the neighbouring plants thanks to the octant sector valves. The cold end of the octant refrigerator appears in figure 12. A remarkable feature is the array of cold rotary compressors raising the pressure of the

return helium vapour to about 100 mbar before entering the refrigerator main exchange line.

5.2 Calculated Performance

Refrigeration performance of the reference design is illustrated in Table 3, for several modes of operation.

In steady operation, with a specific heat load of 0.2 W m^{-1}, 300 W of refrigeration at 1.8 K are produced by pumping a vapour flow of 15 g s^{-1} per half-octant. The corresponding pressure and temperature drops result in a maximum magnet temperature of 1.81 K. In these conditions, the static superfluid helium ducts are sufficient to conduct the steady operation heat load over twice the normal distance, i.e. 39.5 m, in order to cope with the failure or unavailability of one local refrigeration station out of two.

The total installed refrigeration power at 1.8 K has been taken as 750 W per half-octant, in order to absorb 0.5 W m^{-1} and thus permit machine cooldown from 4.5 K to 1.8 K in about 6 hours. Again, the limiting factor is the installed power, and not the conduction through the static superfluid helium.

However, the latter is exploited integrally for recooling a three-magnet string after a quench; a maximum of 2 W m^{-1} can then be extracted from the quenched magnet string, which yields a recooling time of about 1 hour between 4.5 K and 1.8 K.

5.3 Possible Variants

The reference scheme presented above can accommodate several variants, among which (a) the suppression of the beam shields and (b) a larger spacing of the local refrigeration stations, briefly described in the following.

In order to allow initial cooling down of the magnets, the installed refrigeration power at 1.8 K of 0.5 W m^{-1} significantly exceeds the calculated

steady-operation heat load of 0.2 W m^{-1}; it would then be technically possible to suppress the beam shields and absorb up to 0.3 W m^{-1} of beam-induced losses at the 1.8 K level at the cost of increased electrical power consumption. The exact economics of such an issue would depend upon precise budgeting of beam induced losses and operation scheduling of the LHC. In particular, this variant would be particularly attractive in the case of a single-channel collider operating with only one strong hadron beam ($\bar{p}p$ or ep options).

Another variant to the reference design scheme is the doubling of refrigeration station spacing; they would be installed every LHC cell (79 m) instead of every half-cell. The refrigeration performance of the modified scheme would be about the same in steady operation and initial cooling down of the machine. However, limited conduction in static superfluid helium would then be insufficient to permit fast quench recovery. Still, recooling times from 4.5 K to 1.8 K well below 1 hour could be achieved by circulating saturated superfluid helium overflowing from an adjacent refrigeration station along the quenched magnet string, where it would recool at close intervals the static helium; in this fashion, quench recovery would no longer be limited by conduction in static superfluid helium, but only by installed refrigeration power.

Both variants are illustrated in the flow scheme of figure 13.

6. CONCLUSIONS

From this very preliminary study a cryogenic system for the LHC at 1.8 K appears to be possible. The need to distribute refrigeration in a long sloping tunnel is not a source of problems which cannot be solved by the experience gained in already built fairly large helium II installations. However, undoubtedly, the system will be more complex than the corresponding 4.5 K option.

The "price" which has to be paid for a cryogenic system at 1.8 K is:

(a) The overall electrical power required for the refrigeration will be increased. Assuming a heat input into the superfluid helium of

m^{-1}, the electrical power required to produce the 1.8 K refrigeration will be approximately 0.9 MW per octant. To this, of course, the electrical power required for the refrigeration at intermediate temperatures between 1.8 and 300 K shall be added. This power will depend on the design of the cryostat and refrigeration scheme but in any case will be lower or at the most equal to the power specified in the design of the 4.5 K option. The electrical power required in both cases, at 1.8 K and 4.5 K, is given in Table IV.

(b) The free diameter available for the circulating beam will be reduced by reason of the thermal shield.

(c) Re-cooling down time, after a magnet quench, will be somewhat longer than in the corresponding 4.5 K option. However, the extra time needed can be limited (less than one hour) by an appropriate refrigeration scheme.

(d) The magnet cryostat and, in general, the entire cryogenic system will be more complex. In practice a beam shield and additional pipes are required in the magnet cryostat. The refrigerators shall have an extra stage to supply a fraction of the cooling power at 1.8 K. It is difficult to evaluate quantitatively the consequences of this increased complexity without a detailed construction design of the system.

The "gain" of a 1.8 K system is probably to be found in an easier magnet manufacturing, in the fact that Nb-Ti superconductor is readily available and of lower cost and, finally, in the better magnet stability possibly given by the use of superfluid helium. A correct evaluation of this "gain" would certainly require additional design and experimental work.

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8. TABLES

1. Calculated steady-operation heat loads (no contingency)

2. Experimental performance data on existing 1.8 K refrigerators

3. Calculated refrigeration performance of reference design

4. Estimated electrical power consumption

9. FIGURE CAPTIONS

1. Short-sample characteristics of industrially produced Nb-Ti at 1.8 K and Nb_3Sn at 4.2 K.

2. Possible types of beam shields.

3. Principle of refrigeration by conduction through static superfluid helium.

4. Chart of heat transport in circular pipes through static superfluid helium between 2.0 K and 1.8 K.

5. Refrigeration scheme with distributed magnetic-cycle refrigerators.

6. Refrigeration scheme with concentrated gas-cycle refrigerators.

7. Cooling down scheme.

8. Principle of gas-cycle refrigerators.

9. Entropy diagram of gadolinium-gallium garnet (GGG) with superimposed Carnot cycle.

10. Reference design, standard half-cell flow-scheme.

11. Reference design, standard cryostat cross-section.

12. Reference design, octant flow-scheme.

13. Reference design, variant with full-cell magnet string length, fast recooling and no beam shield.

TABLE I - CALCULATED STEADY OPERATION HEAT LOADS (No contingency)

HEAT LOAD PER UNIT LENGTH (W m^{-2})	SUPERFLUID HELIUM CRYOGENIC SYSTEM			CONVENTIONAL HELIUM CRYOGENIC SYSTEM	
	90 K	4.5 K	1.8 K	90 K	4.5 K
Radiation	5.0	0.02	0.08	5.0	0.1
Conduction through residual gas	0.1	0.01	0.01	0.1	0.02
Conduction along supports	1.5	0.15	0.01	1.5	0.1
Valves and piping	0.4	0.16	0.01	0.4	0.16
Beam induced losses	-	0.29	0.01	-	0.3
Resistive joints	-	-	0.05	-	0.15
Current feedthrough	-	-	0.01	-	-
Total	7	0.7	0.2	7	0.9

TABLE II - EXPERIMENTAL PERFORMANCE DATA ON EXISITNG 1.8 K REFRIGERATORS

REFRIGERATOR	POWER AT 1.8 K (W)	GRID POWER $P_{1.8}$ (KW)	POWER AT 4.5 K (W)	GRID POWER $P_{4.5}$ (KW)
Karlsruhe (Linde)	340	690	400	557
Karlsruhe (MG)	370	436	350	230
Stanford	300	440	-	-
CERN (BOC)	300	725	400	500

TABLE III - CALCULATED REFRIGERATION PERFORMANCE OF REFERENCE DESIGN

MODE	STEADY OPERATION	FINAL [2] COOLDOWN	RECOOLING AFTER QUENCH OF HALF CELL
Heat load (W m^{-1})	0.2	0.5	2.0 [3]
Refr. power per station (W)	7.9	19.8	43.5
Refr. power per half-octant (W)	300	750	370
He flow per half-octant (g)	15	37.5	18.5
Max. refr. [1] station temp. (K)	1.80	1.89	1.81
Max. magnet [1] temperature (K)	1.81	1.91	2.17

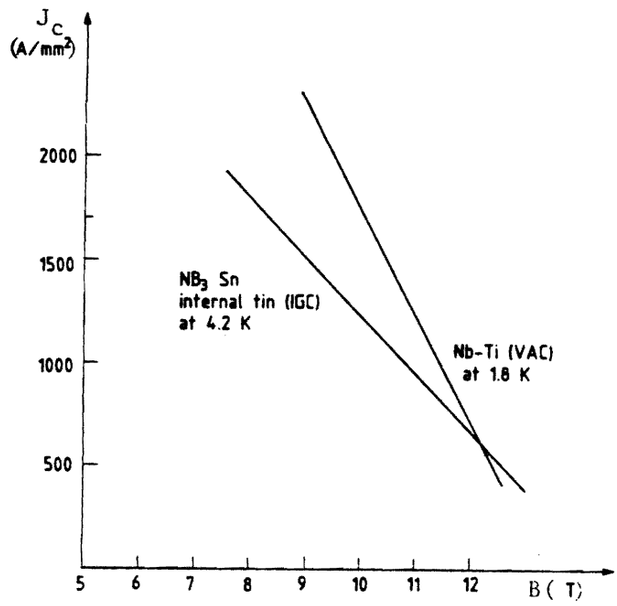
[1] Assuming 15 mbar suction pressure at cold compressor and 2 m Km^{-1} thermal resistance at refrigerator station

[2] Corresponding to maximum installed power

[3] Limited by conduction in static superfluid helium

TABLE IV - ESTIMATED ELECTRICAL POWER CONSUMPTION

	Superfluid helium cryogenic system			Conventional helium cryogenic system	
	90 K	4.5 K	1.3 K	90 K	4.5 K
Steady operation heat load (W m^{-1})	7	0.7	0.2	7	0.9
Heat load per octant (W)	23300	2330 ±1 6 gs	600	23300	3000 ±1 6 gs
Refr. efficiency	20	600	1500	20	600
Equivalent grid power (MW)	0.47	1.76	0.90	0.47	2.16
Steady operation power per octant (MW)	3.1			2.6	
Installed power per octant (MW)	7.8			6.5	


J_c
(A/mm²)
2000
1500
1000
500
5
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7
8
9
10
11
12
B (T)
NB_3 Sn
internal tin (IGC)
at 4.2 K
Nb-Ti (VAC)
at 1.8 K

Fig.1

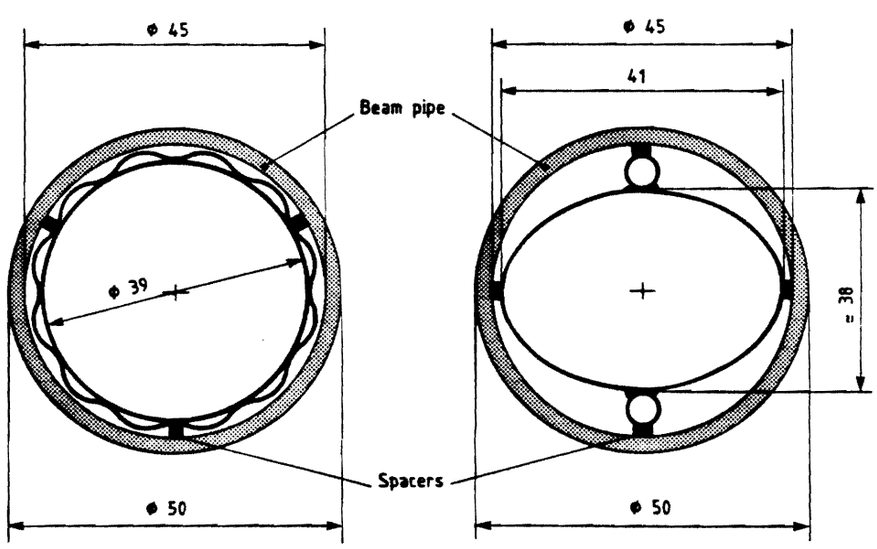

ϕ 45
ϕ 45
41
Beam pipe
ϕ 39
≈ 38
Spacers
ϕ 50
ϕ 50

Fig.2

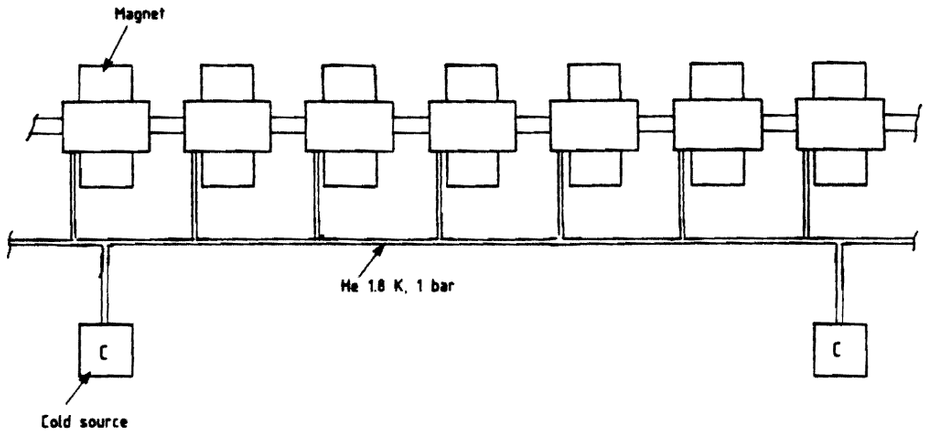

Magnet
He 1.8 K, 1 bar
C
C
Cold source

Fig.3

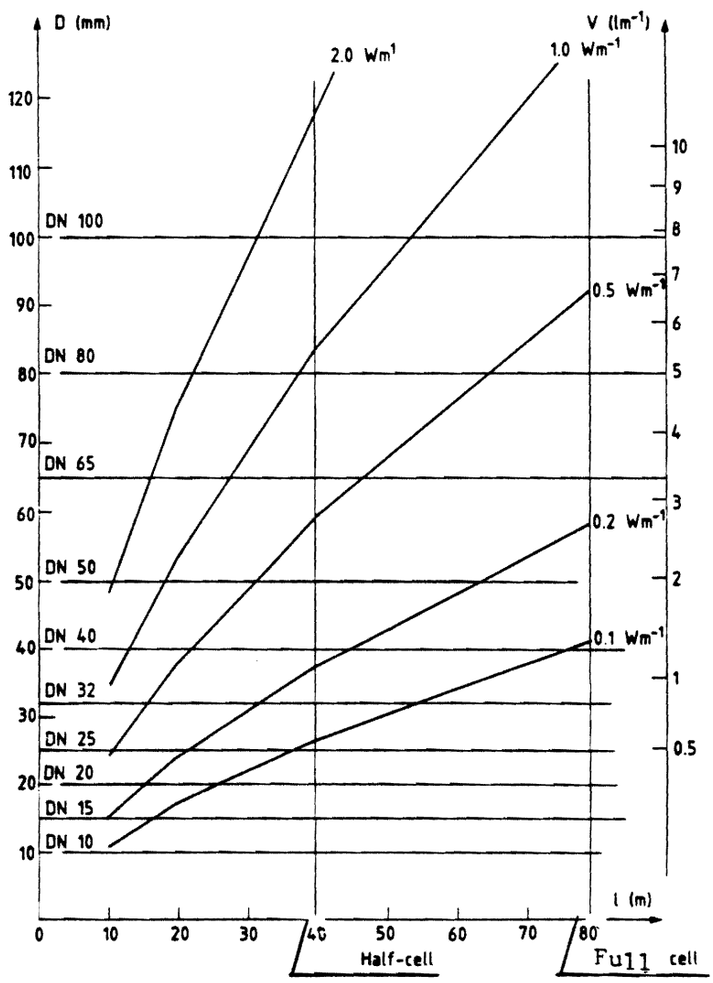

D (mm)
V (lm⁻¹)
2.0 Wm⁻¹
1.0 Wm⁻¹
0.5 Wm⁻¹
0.2 Wm⁻¹
0.1 Wm⁻¹
DN 100
DN 80
DN 65
DN 50
DN 40
DN 32
DN 25
DN 20
DN 15
DN 10
l (m)
Half-cell
Full cell

Fig.4

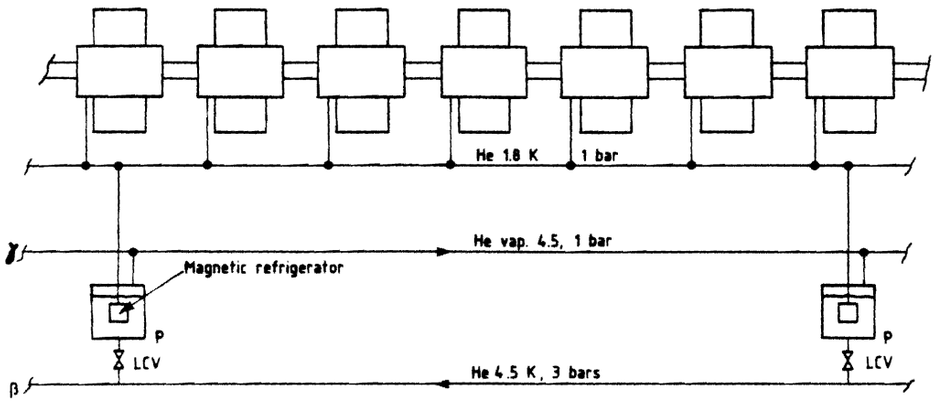

He 1.8 K
1 bar
He vap. 4.5, 1 bar
Magnetic refrigerator
P
LCV
P
LCV
He 4.5 K, 3 bars
β

Fig.5

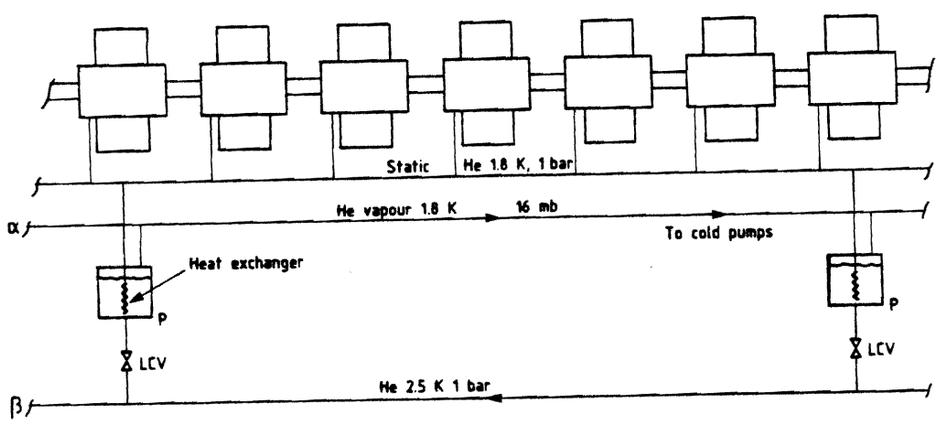

Static
He 1.8 K, 1 bar
He vapour 1.8 K
16 mb
To cold pumps
α
Heat exchanger
P
LCV
P
LCV
He 2.5 K 1 bar
β

Fig.6

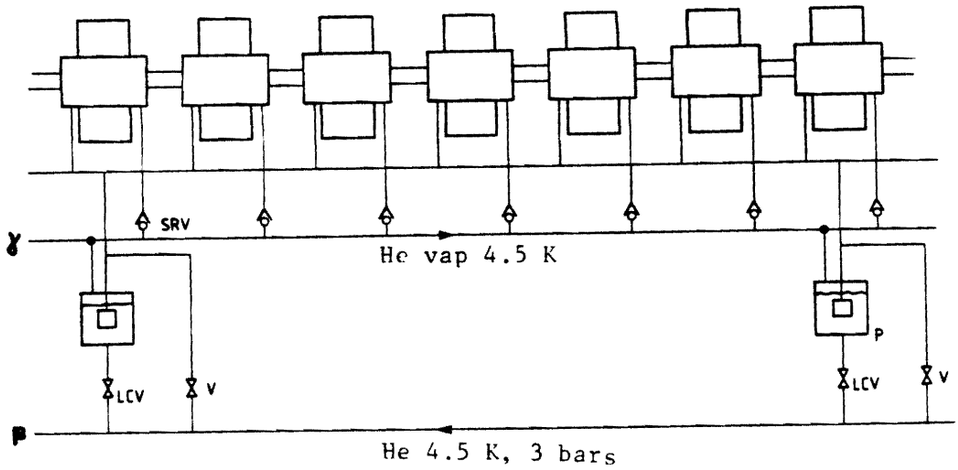

SRV
γ
He vap 4.5 K
P
LCV
V
LCV
V
β
He 4.5 K, 3 bars

Fig.7 a

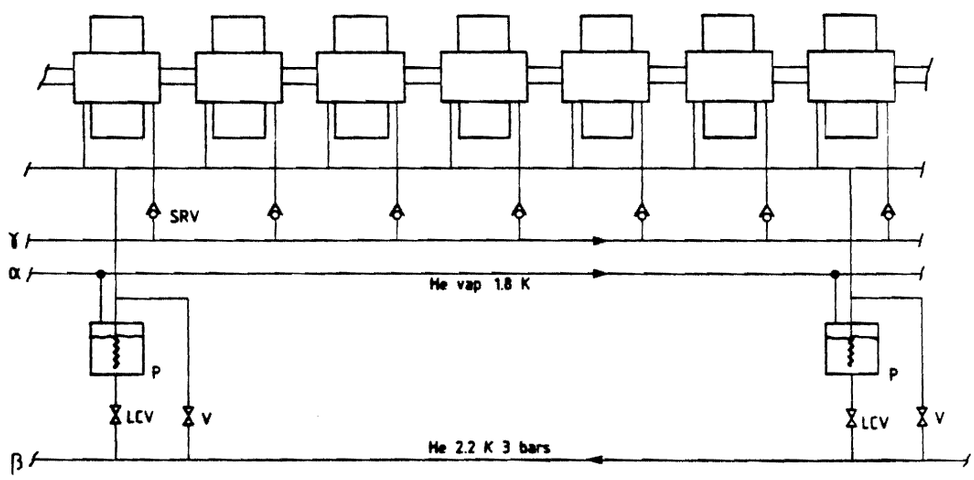
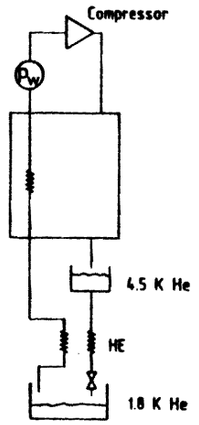
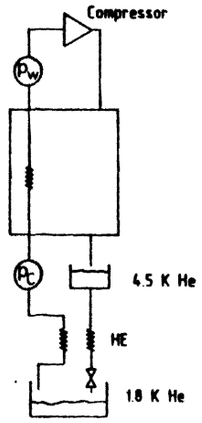

SRV
γ
α
He vap 1.8 K
P
P
LCV
V
LCV
V
β
He 2.2 K 3 bars

Fig.7 b


Compressor
Pw
4.5 K He
HE
1.8 K He

(a)


Compressor
Pw
Pc
4.5 K He
HE
1.8 K He

(b)

Fig.3

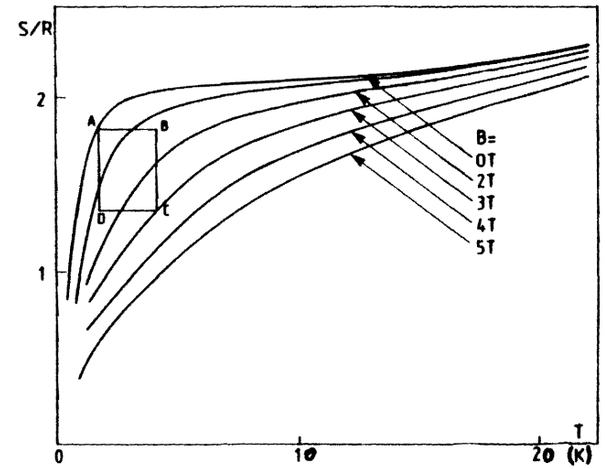

S/R
2
1
A
B
C
D
B=
0T
2T
3T
4T
5T
0
10
20
T
(K)

Fig.9

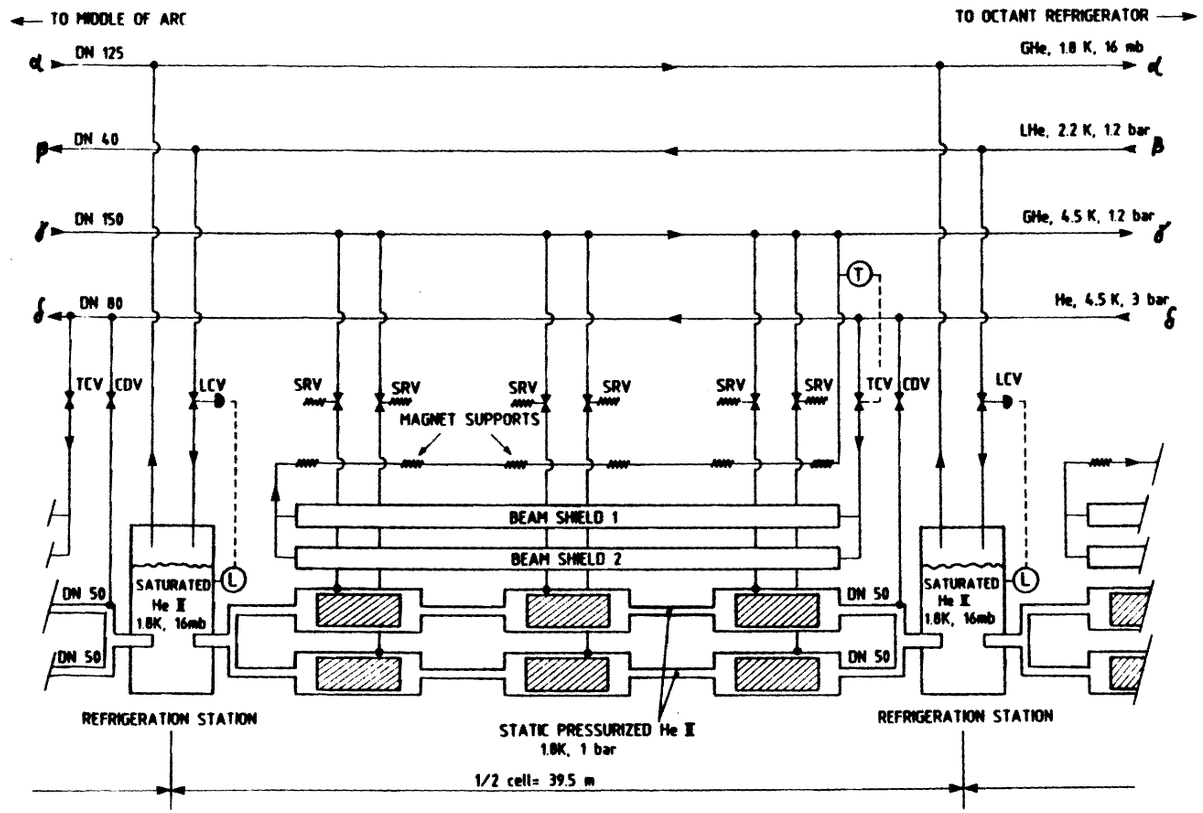

TO MIDDLE OF ARC
TO OCTANT REFRIGERATOR
DN 125
GHe, 1.8 K, 16 mb
DN 40
LHe, 2.2 K, 1.2 bar
DN 150
GHe, 4.5 K, 1.2 bar
DN 80
He, 4.5 K, 3 bar
TCV
CDV
LCV
SRV
MAGNET SUPPORTS
BEAM SHIELD 1
BEAM SHIELD 2
SATURATED He II 1.8K, 16mb
DN 50
REFRIGERATION STATION
STATIC PRESSURIZED He II 1.8K, 1 bar
1/2 cell= 39.5 m

Fig.10

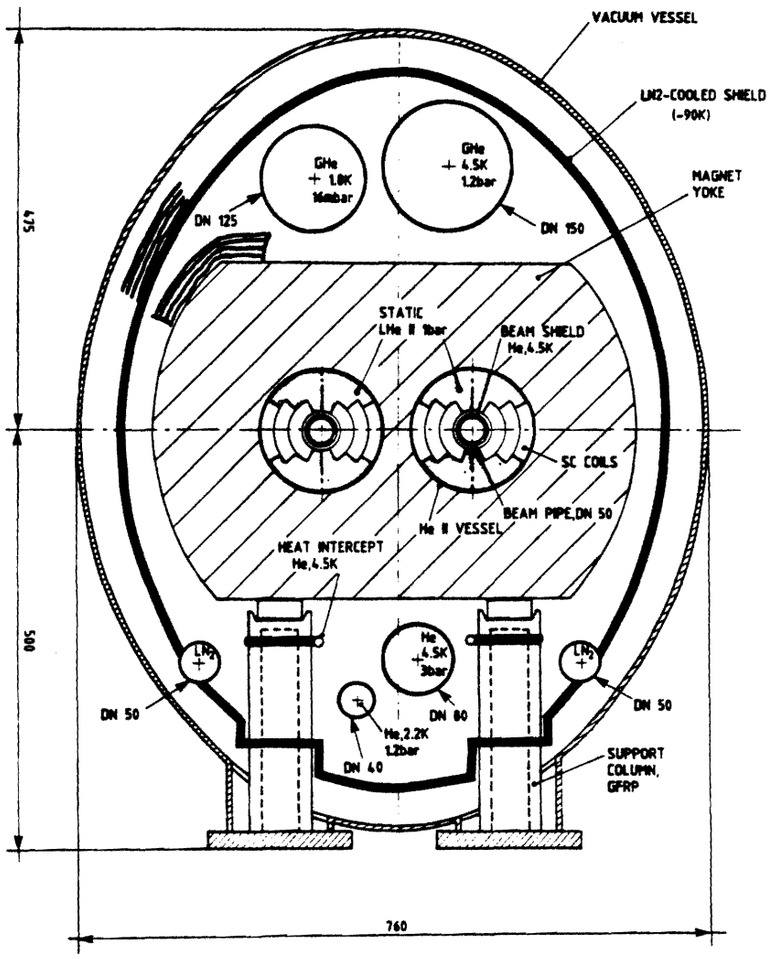

VACUUM VESSEL
LN2-COOLED SHIELD
(-90K)
GHe
+ 1.8K
16mbar
GHe
+ 4.5K
1.2bar
MAGNET
YOKE
DN 125
DN 150
475
STATIC
LHe II 1bar
BEAM SHIELD
He,4.5K
SC COILS
BEAM PIPE,DN 50
He II VESSEL
HEAT INTERCEPT
He,4.5K
500
He
+4.5K
3bar
LN2
LN2
DN 50
DN 50
DN 80
He,2.2K
1.2bar
DN 40
SUPPORT
COLUMN,
GFRP
760

Fig.11

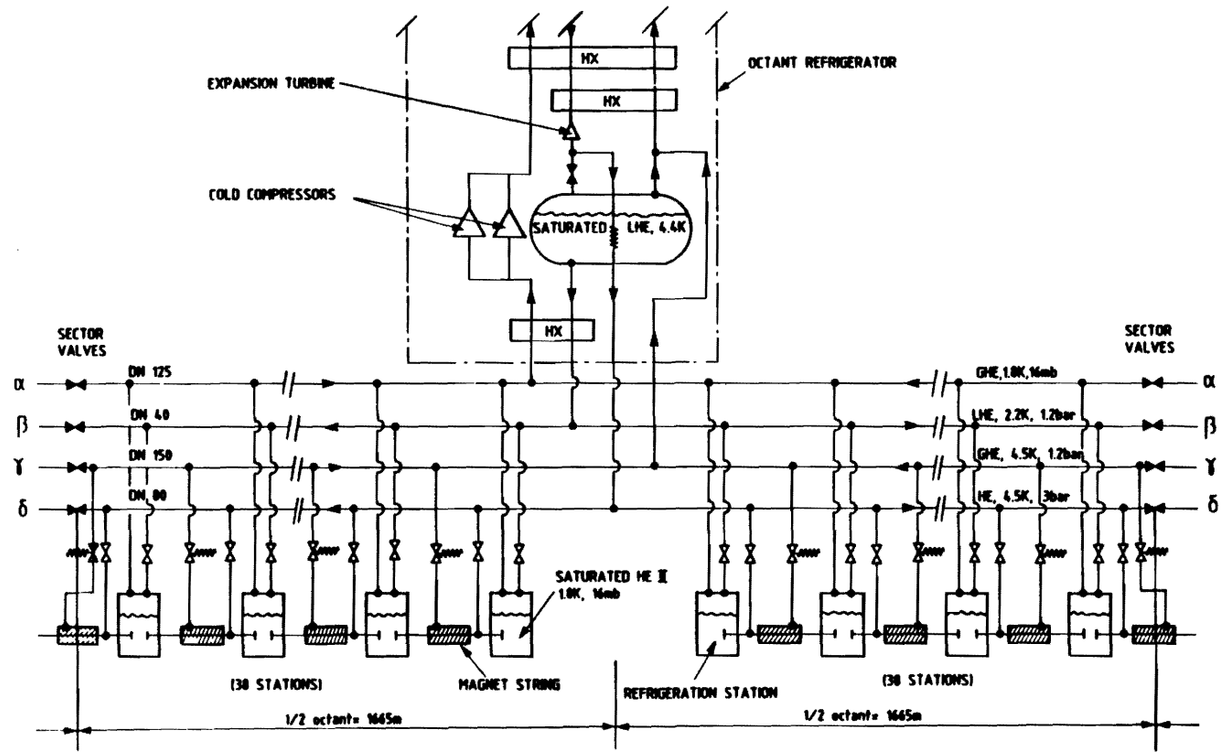

EXPANSION TURBINE
COLD COMPRESSORS
HX
HX
HX
OCTANT REFRIGERATOR
SATURATED LHE, 4.4K
SECTOR VALVES
SECTOR VALVES
α
β
γ
δ
DN 125
DN 40
DN 150
DN 80
GHE,1.8K,16mb
LHE, 2.2K, 1.2bar
GHE, 4.5K, 1.2bar
HE, 4.5K, 3bar
SATURATED HE II
1.8K, 16mb
(30 STATIONS)
MAGNET STRING
REFRIGERATION STATION
(30 STATIONS)
1/2 octant= 1665m
1/2 octant= 1665m

Fig.12

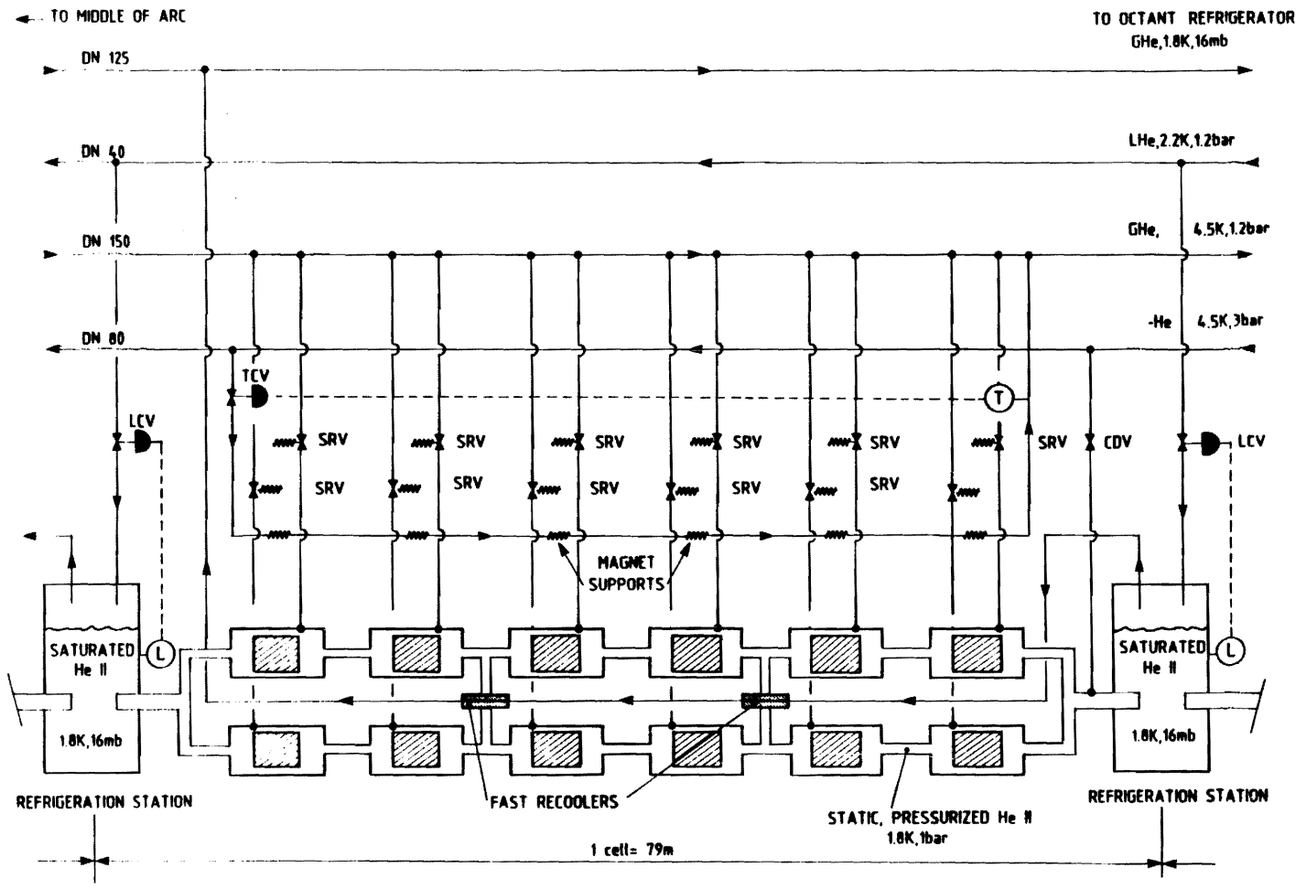

TO MIDDLE OF ARC
TO OCTANT REFRIGERATOR
GHe,1.8K,16mb
DN 125
DN 40
LHe,2.2K,1.2bar
DN 150
GHe, 4.5K,1.2bar
DN 80
-He 4.5K,3bar
TCV
LCV
SRV
CDV
T
L
MAGNET SUPPORTS
SATURATED He II
1.8K,16mb
REFRIGERATION STATION
FAST RECOOLERS
STATIC, PRESSURIZED He II
1.8K,1bar
1 cell= 79m

Fig.13