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THE TORE SUPRA HeII CRYOGENIC SYSTEM

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The tokamak TORE SUPRA built by the association EURATOM-CEA is routinly operated with a toroïdal magnet made of Niobium Titanium cooled at 1.8 K by pressurized HeII.
The paper will remind the reasons for such a choice and will describe the corresponding technical solutions.
After several years of operation, the validity of the HeII cooling solution will be discussed on the basis of the actual and long term behaviour.

1. Introduction

Since its discovery 52 years ago, superfluid helium (HeII) was mainly considered as a curiosity by low temperature physicists and was used as a means to produce temperature as low as 1 K.

Its suprising ability to climb the walls of a reservoir or to flow apparently without any resistance through very narrow leaks explain the reluctance to use such a fluid for practical applications.

With the appearance of industrial superconductors with critical temperature near 10 K, the possible operation near 2 K rather than 4.5 K was soon considered.

Unfortunately, the first experiments using superconducting coils in an helium bath under reduced pressure were generally deceiving due to the very poor dielectric properties of low pressure gazeous helium.

A completely new situation was introduced by ROUBEAU [1] who proposed a solution to implement superfluid helium at atmospheric pressure at the λ transition, opening the way to further development of pressurized superfluid bath at any desired temperature and pressure pioneered by the Grenoble group [2].

By the end of 1991 a large fusion tokamak called TORE SUPRA has been operating for about 3 years by using pressurized HeII cooling as an industrial solution [3].

2. Why pressurized HeII ?

As shown in fig. 1, the phase diagram of helium exhibits no triple point but a solid line existing above about 25 bars, a liquid vapor equilibrium curve dropping near 10 mb at about 1.8 K and in between, a phase transition (the so called λ line) from normal helium (HeI) to superfluid helium (HeII). The highest temperature for this transition is on the liquid vapor curve at 2.172 K also called lambda temperature (T_λ).

2.1. Implementation of pressurized HeII [2]

In order to get any working point in the HeII region and to avoid liquid vapor equilibrium conditions, means to impose separately T and P have to be provided as shown in the fig. 2.

The main characteristic of the double bath technique relies in the proper design of the necessary fluid connection between the two different temperature baths HeI and HeII in such a way that results a low enough heat flux to allow the desired thermal gradient.

For practical applications, such a solution provides :

- Easy access to HeII (no tight barrier).
- No risk of air leakage.

- Similarity to a standard HeI cryostat as far as dielectric properties and liquid supply are concerned.
- Heat load mainly derived at 4.2 K from current leads, supports, shielding, etc...

2.2. Practical heat transfer in superfluid helium

2.2.1. Stationay heat transfer [5,6,7]

In pressurized superfluid helium, there is no natural convection nor any nucleate boiling. Instead, heat is transported by a counterflow process, known as the Gorter Mellink regime, quite well described within the framework of the two fluid theory.

The heat flux density can be expressed by the following equaquation :

$$q = [f(T)dT/dx]^{1/m} \text{ with } m \simeq 3.4$$

The conductivity function f(T) starts from zero at OK, passes through a fairly broad maximum near 1.9 K and drops to zero again at the lambda temperature.

The heat flux flowing in a channel of a given geometry is finally only limited by the temperature difference between the two channel ends.

Here, the superiority of the pressurized fluid is cleary evident as the warm end temperature can be increased up to the λ transition.

On the contrary, in a saturated HeII bath, the maximum allowed temperature is controlled by the hydrostatic pressure and temperature differences of only few hundredth of a K can be obtained.

When a solid material has to be cooled by HeII the main temperature difference is concentrated at the solid liquid boundary governed by the Kapitza resistance.

Practical data for Kapitza resistance with industrially prepared copper and aluminium are given in references [8], [9].

2.2.2. Transient heat transfer

Significant experiments are reported in reference [10].

As shown in fig. 3, the specific heat of superfluid helium exhibits a very pronounced anomaly at the HeII transition. Typical value of 4 to 6 J g^{-1} K^{-1} for HeII have to be compared with specific heat for copper or NbTi alloys which are at 4.2 K around 10^4 times smaller. From this fact HeII can act as a very efficient thermal reservoir able to store fairly large amount of energy mainly when pressurized fluid is used.

- From 1.8 K to 1.82 K corresponding to typical limits with saturated HeII the enthalpy difference is 9 $mJ.cm^{-3}$.
- From 1.8 K to 2.16 K corresponding to operation at 1 bar the enthalpy difference is 280 $mJ.cm^{-3}$ noticeably larger.

A very high heat capacity associated with a very good ability to transport heat without significant temperature rise explain the large advantage of cooling superconductors by pressurized HeII when high level perforr ces are required.

2.3. Stability of superconductor operation

This high potentiality is shown effective in experiments where a superconductor is tested in a background field up to 12 Tesla in a bitter magnet [11].

A prototype monolithic NbTi conductor 2.5 x 5.6 mm proposed for TORE SUPRA was wound in a one layer solenoid and cooled on its two large side faces by vertical channels 20 cm long and 1.8 mm thick with 1 cm wide spacers covering 50 % of the surface area. Small heaters were located under spacers to simulate some disturbances inducing a normal zone. The results of the test performed comparatively in HeI and HeII are summarized in fig. 4 where the stable limit for conductor current is plotted versus the background field for different values of locally deposited energy.

The diagram clearly shows the possibility for the considered NbTi conductor to work safely at 1500 A current and field level of 10 or 11 Tesla when cooled by pressurized HeII. When the same conductor is cooled by boiling HeI, the current has to be reduced by a factor of two and the field lowered to less than 9 Tesla.

3. The fusion tokamak TORE SUPRA [12]

3.1. General presentation

This medium sized tokamak (large radius 2.37 m, plasma radius 0.75 m) the construction of which was approved in 1981 has been operated since April 1988 by EURATOM-CEA Association at Cadarache Nuclear Research Centre in south east of France.

The following very stringent specifications were imposed on the design of the superconducting toroidal magnet :

peak field on the conductor, 9 T (4.5 T on the axis), current density in the winding 50 $A.mm^{-2}$, superimposed field variations of about 0.5 T in 10 ms.

HeII cooling was adopted for two reasons :

- Industrial availability of NbTi rather than risk associated with Nb_3Sn.

- Capability to reduce the copper cross section in the conductor (100 $A.mm^{-2}$) to fullfill stability criterion as well as low energy deposition by pulsed field.

The ohmic heating coil and the poloidal magnet are based on water cooled copper of conventional technology.

The toroidal magnet [13] is made of 18 NbTi coils cooled by pressurized HeII at 1.8 K ; they are in mutual contact and constitute a vault in which all the electromagnetic forces are sustained at low temperature.

The mass of the 1.8 K part of the 18 coils is about 50 000 kg.

Around each winding, a thick stainless steel casing provides the required mechanical strength and acts as a magnetic shield against rapid field variations. This mechanical structure of about 120 000 kg is cooled near 4.5 K.

Around the coils, a radiation shield of about 20 000 kg is cooled between 80 K and 100 K.

The cryogenic system has been extensively described elsewhere [14], [15] and only the main particularity will be discussed here.

The pressurized helium II circuit represented in fig. 5 corresponds to one of the 18 coils identical but thermally independant one from the other.

The monolithic 1 500 A NbTi conductor (100 $A.mm^{-2}$) of a rectangular cross section area of 2.8 x 5.6 mm is wounded in double pancakes separated by 1.8 mm thick insulating spacers.

Each coil filled by about 160 litres of pressurized HeII (4 500 l in the tokamak) is connected to the cold source (at the bottom) by a 74 mm diameter about 10 meter long tube in which the electrical leads are included (coming from the HeI cryostat at the right top). For a heat load of 15 watts per coil, the temperature difference in the 74 mm pipe is 0,05 K.

The cold source designed to remove 300 W at 1.75 K is a low pressure bath fed by a Joule Thomson loop represented in fig. 6.

By comparison with the previous HeII refrigerators of the same power level, a completely new pumping system was chosen for TORE SUPRA. A first step of pumping from 13 mbar to 80 mbar is performed at low temperature by two stages of cold pumps : a new industrial feature and a very important one.

At a 80 mbar pressure level, the design of the low pressure heat exchanger becomes easy and the size of the final pumping stage gives access to reliable components.

For the cold pumps, centrifugal machinery supported on magnetic bearing is driven by high frequency electric motors. In the first stage a 120 mm diameter wheel rotates at 25 000 rev.min^{-1} In the second stage a 80 mm diameter wheel rotates at 40 000 rev. min^{-1}.

For warm pumping, two stages of oil liquid ring pumps were selected for their high potential reliability. The oil is the same as in the screw compressors of the 1 000 W HeI refrigerator

The cryogenic load breakdown with only 300 W at 1.8 K with respect to about 1 000 W at 4.2 K leads to an admissible level of power consumption of about 1.25 MW.

3.3. Performances and long term behaviour of the 1.8 K refrigerator : [16], [17], [18]

The TORE SUPRA cryogenic system was built then tested and operated with the schedule given in table 1.

The cryogenic power given by the refrigerator was measured and compared to the specified values as given in the table 2.

At HeII level, temperatures lower than expected was measured and at HeI level an extra liquefaction rate of about 3 $g.s^{-1}$ was simultaneously obtained.

On the cryogenic lines and satellites some unexpected 200 W extra load was initially obtained in excess of the 750 calculated watts.

This problem was due to bad cooling for some shields or some exhaust pipes using only 80 K heat sink made by copper strips and mechanical contact.

By the middle of 1989, we improved cooling by a cold gaz circulation and got a more satisfying situation.

A failure analysis discussed in the reference [18] exhibits for the first half of 1990, 18 incidents responsible of 41 hours of plasma experiments down time.

By now this performance has been still improved by a systematic programm of preventive maintenance.

The long term behaviour of the pumps and compressors is summurized in the table 3.

The pumping system with two stages of centrifugal pump working from 4 K to 15 K and two stages of oil pumps at room temperature has been operated for more than 10 000 hours without any trouble. The choice of frictionless and valveless solutions can be confirm as a comfortable and reliable means of producing HeII refrigeration.

The compressor set made of two stages of two parallel STAL screw compressors has been operated for about 30 000 hours with very stable performances.

On the second stage some unusual value of the isothermal efficiency was detected and can be explained by a quite high longitudinal clearance in combination with an unperfect shape of a screw contributing to reduce his working length.

More severe and unexpected was the systematic trouble coming from the needle bearings of the electrical motors driving the compressors.

Life time as low as 4 000 hours was suprisingly obtained, very far from the expected 40 000 hours.

The main reason for that seems to be due to vibration applied to the machine at rest by transportation or within standby period.

Means to avoid free movement of the rotor at rest are then recommended as well as very strict procedure for maintenance and control including systematic motor bearing replacement every two years.

Finally, a very important parameter, frequently neglected in the initial phase of a project is the fluid consumption to be taken into account.

Gas losses are not only important by the corresponding cost but also because a leak is generally associated with a circuit pollution.

In the case of TORE SUPRA the helium consumption started in 1988 from 10 000 liters per month of liquid helium. With more and more experience and a systematic maintenance program, it decreases to 3 000 l a month in 1990 then 2 000 l a month in 1991. The lower expected value can be estimated around 1 000 l a month.

Fror such a figure, one can say it is more easy to found elegant solutions for the part of the system operated at 1.8 K than for the circuitery working at room temperature.

4. Conclusion

The efficiency and the nigh capacity of HeII cooling has been demonstrated in a large scale by the operation at nominal performances of the TORE SUPRA toroïdal magnet.

The associated HeII cryogenic system and refrigerators works very satisfactorily and have been operating for more than 3 years with the same constraints than any other components of the tokamak machine.

For large projects in the 10 Tesla range, HeII cooling and HeII technology can now be considered as a qualified alternative for which industrial solutions are available.

5. Acknowledgement

This paper was written with the help of the group in charge with the construction then the operation of the TORE SUPRA HeII cryogenic system.

The high quality level and the high performances of this challenging project were only possible by joining efficient efforts from all the team members.

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1981			Official acceptance
			Detailed design : Lines + Satellites
1982			Preliminary discussion with industry
			+ critical components development.
1983			Main orders to industry
1984			
1985			
1986	october	(	
	february	)	Commissioning test for refrigerator
	may	(	
1987	july	)	+ Lines and Satellites
1988	march		First cooling of toroïdal magnet
1989	april	(	
	august	)	One toroïdal coil to be replaced
1990			
1991			More than 3 years of routine operation

Table 1 : Time table for the cryogenic system

	HeII	HeI		80 K	Electrical consumption
	Watt	Watt	LHe $g.s^{-1}$	Watt	kW
Specified power	300 at 1.75 K	745 at 4 K	3	10700	1120
	320 at 1.8 K	970 at 4 K	0	10700	
Measured value at the coldbox	300 at 1.72 K	745 at 4 K	4.75	10700	1250
	320 at 1.75 K	970 at 4 K	2.7	10700	1250

Table 2 : Performances of the refrigerator

		July 86 Flow g/s	July 86 Efficiency	Oct 90	Sept 91 Flow g/s	Sept 91 Efficiency	Working time H
cold comp.	C1	12	360 W		12	360 W	bearings 30 000
	C2	12	400 W		12	400 W	motor 10 000
warm pump	P1	16,7 at 50 mb	204 kW		15,7 at 50 mb	204 kW	12 100
	P2	88 at 612 mb	113 kW		88 at 612 mb	113 kW	16 200
screw comp.	C1	107	0,567		107	0,567	30 630
	C2	106	0,54		104	0,565	28 127
	C3*	131	0,457	New bearings + Clearance reduction after 23 700 H	144	0,507	30 704
	C4	223	0,56		235	0,59	30 574

*Unperfect machining of the screws at the HP side.

To be changed at the end of 1991.

Table 3 : Long term behaviour of pumps and compressors

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Figure Captions

Figure 1 : Phase diagram of helium.

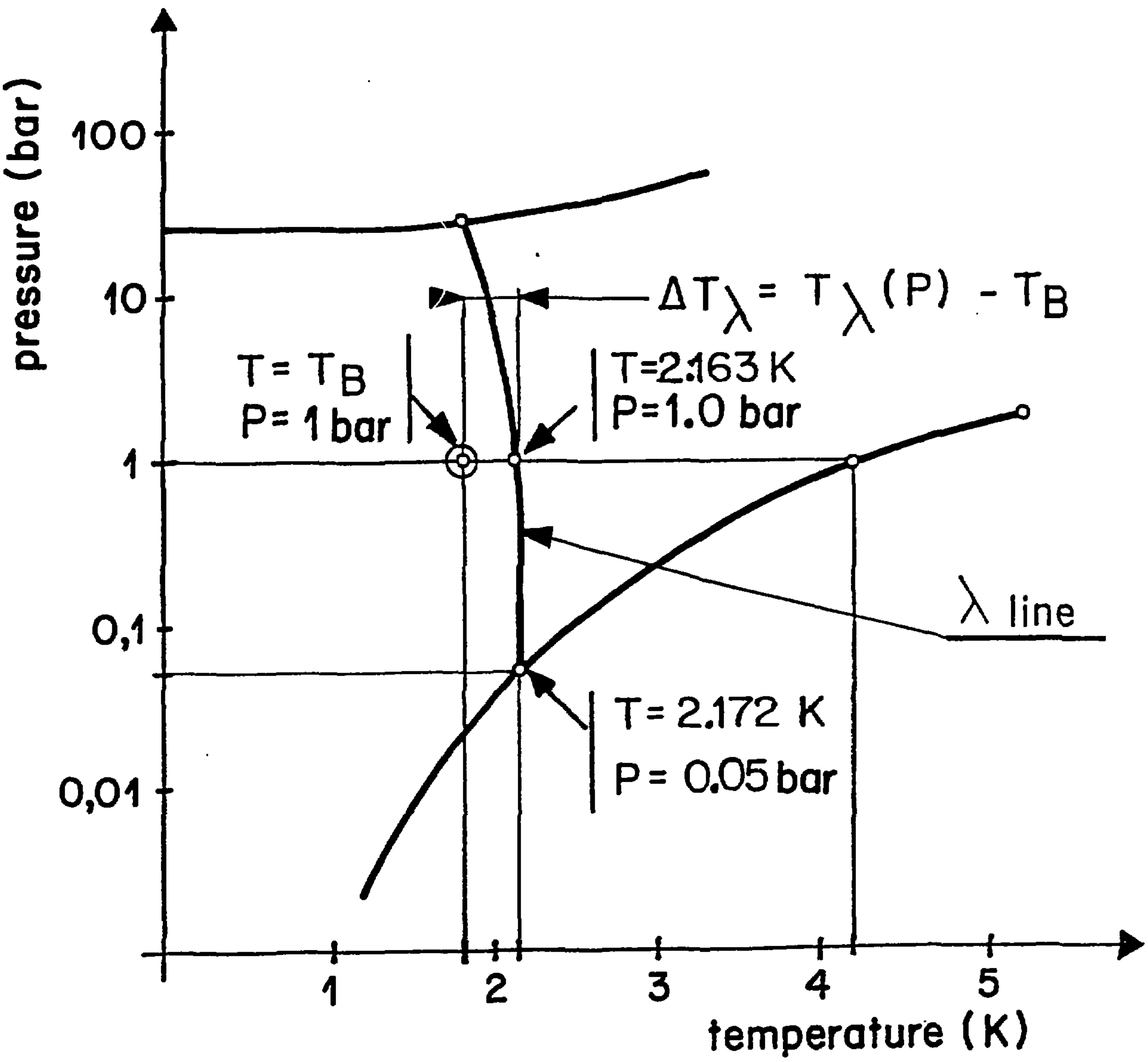
Figure 2 : Double bath technique for $T < T_{\lambda}$.

Figure 3 : Specific heat of HeII.

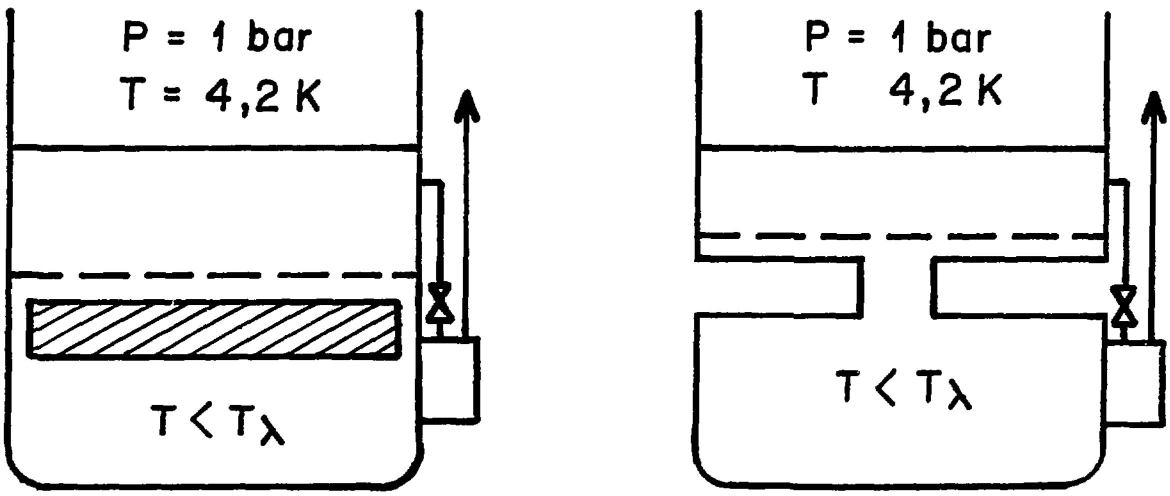
Figure 4 : Stability test with TORE SUPRA conductor.

Figure 5 : Cross section of the cryogenic supply of each TORE SUPRA coil.

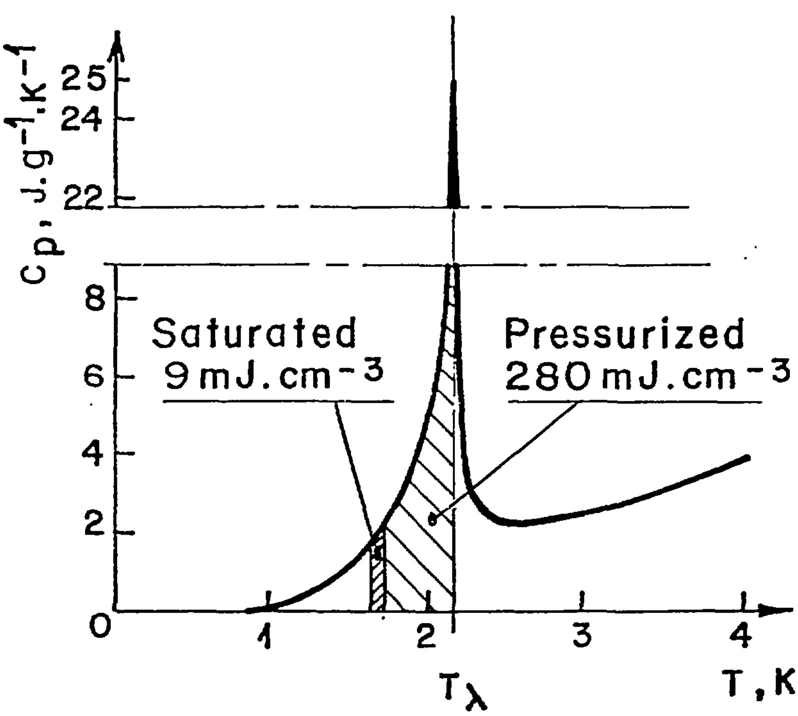
Figure 6 : HeII refrigerator.



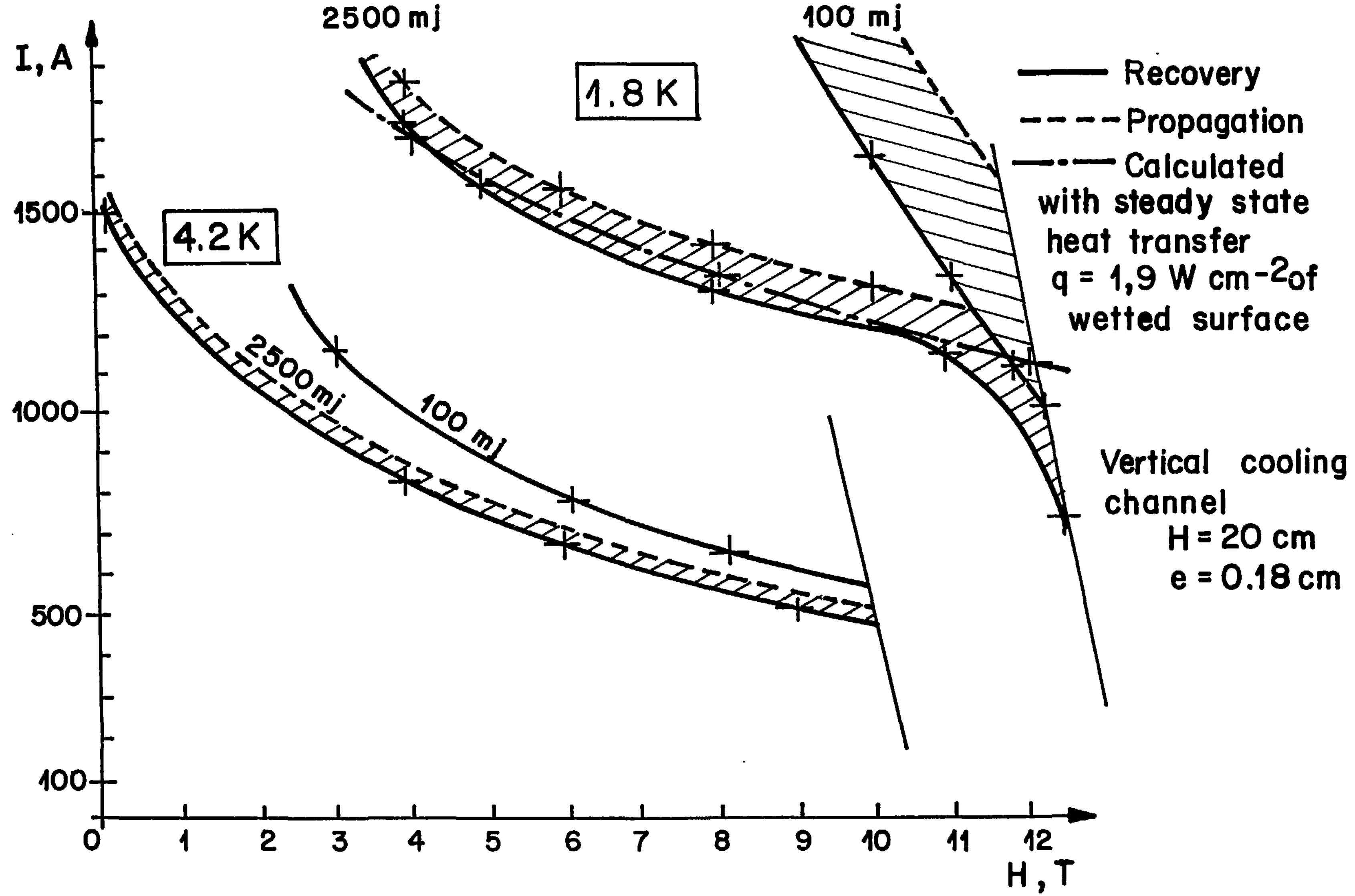
G. CLAUDET Figure 1



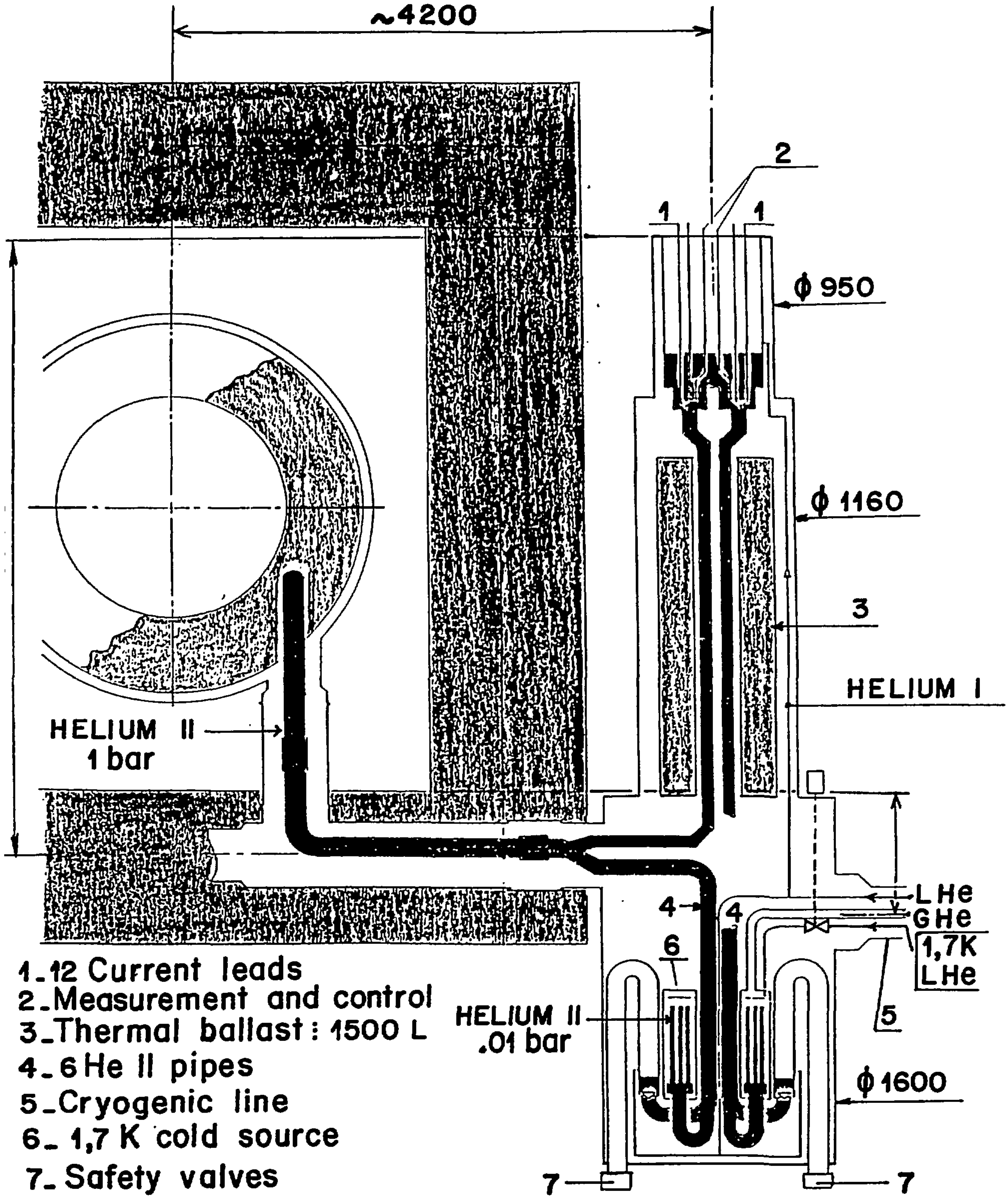
G. CLAUDET Figure 2



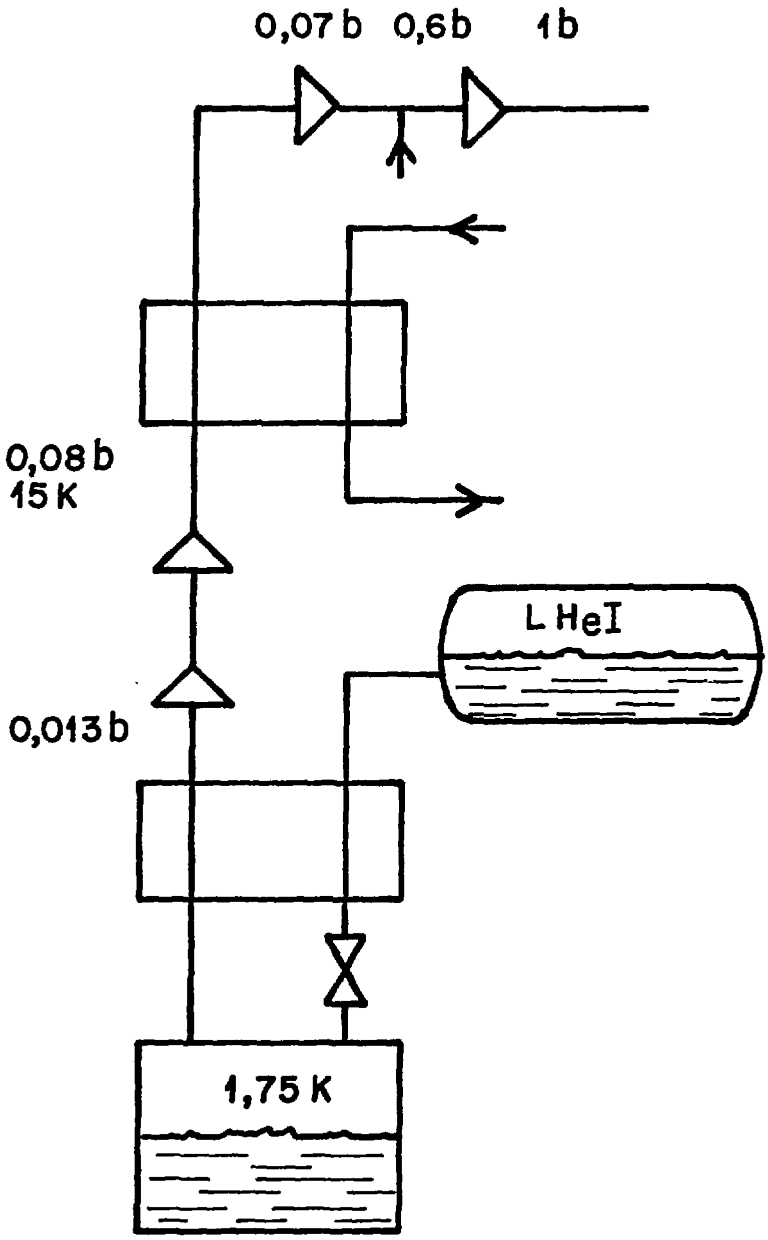
G. CLAUDET Figure 3



I, A
1500
1000
500
400
0
1
2
3
4
5
6
7
8
9
10
11
12
H, T
2500 mj
100 mj
1.8 K
4.2 K
2500 mj
100 mj
Recovery
Propagation
Calculated
with steady state
heat transfer
q = 1,9 W cm-2of
wetted surface
Vertical cooling
channel
H = 20 cm
e = 0.18 cm



G. CLAUDET figure 5



G. CLAUDET figure 6