The Cryogenics for the TT2A Magnet

J. R. J. Bennett and Y. Ivanyushenkov (RAL)
(DRAFT, Feb. 9, 2005)

1.0 Introduction.

An attempt is made to write down the logical sequences of events that have led to the present design of the cryogenic piping system.

The "specification" is:

1. Initial fill of the magnet cryostat slowly over many hours -12 hours
2. Operation of the magnet on the following cycle:

- When the magnet is at ~80 K, empty the cryostat and neighbouring beam lines, to prevent activation by the beam, in ~2-3 minutes.
- After activation of the magnet, ~10 s, cool the magnet with LN2 to ~80 K in ~30 minutes or less.

2.0 The CERN Meeting, 4 November

At the meeting in CERN on 4 November we agreed that the cryogenic system could be as shown in Figure 1.

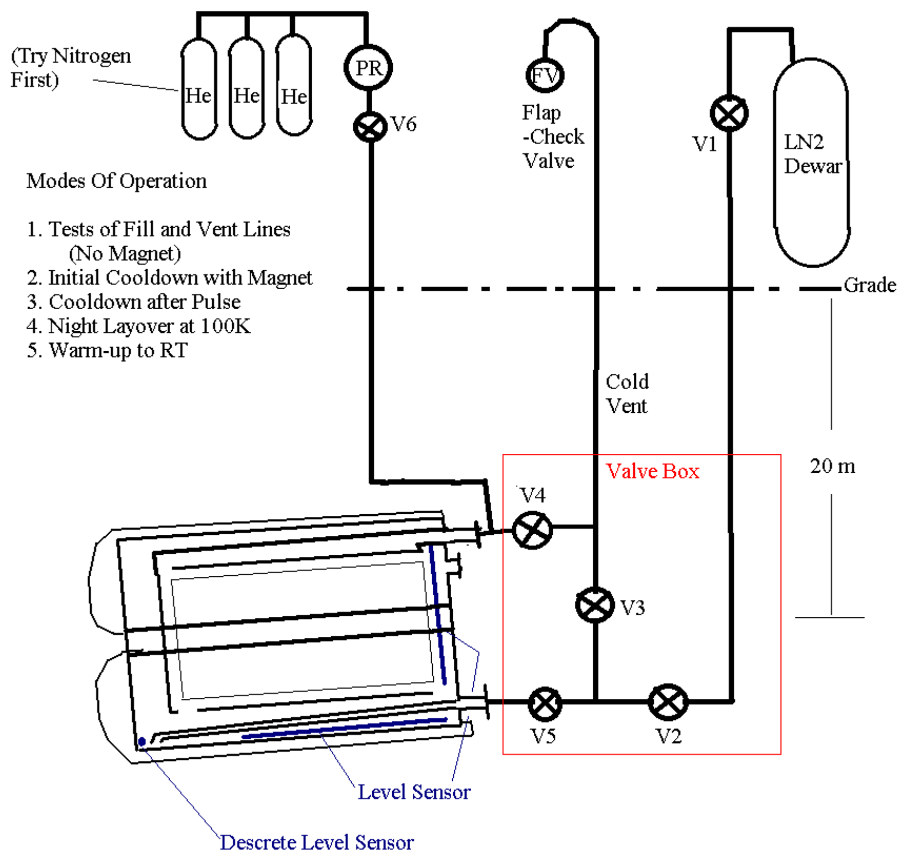

Figure 1. Schematic diagram of the cryogenic system to cool the 15 T pulsed solenoid magnet (drawn by Peter Titus). The LN2 is emptied from the cryostat onto the ground through the vent pipe.

There were a number of issued discussed and these are summarised in Friedrich Haug's note of 9 November 2004, which is reproduced in Appendix 1. Some of the issues concerning the overall design of the flow system are summarised below:

1. LN2 can be vented onto the ground. Thus:
   - It is not necessary to return the nitrogen to the storage Dewar.
   - No heater required in the vent line so that warm nitrogen enters the atmosphere.
2. The magnet need only be cooled to ~80 K. Thus:
   - No LN2 sub-cooling and vacuum pump is required.

2.1 Operation of the System

The operation of the system was envisaged as follows. All valves are remotely operated.

2.1.1. To fill the cryostat from ~300 K

This operation need not be quick. A fill time of hours is quite acceptable and reduces thermal stresses on the magnet. The valve positions are as shown in the table. Valve V2 is adjustable so that the flow is controlled. The amount that the valve is allowed to open will be determined by the rate of cooling that is required. When the level gauge shows that the cryostat is full the control valve, V2, will automatically close and open to maintain the level.

Valve	Position
V1	open
V2	control open
V3	closed
V4	open
V5	open
V6	closed

2.1.2. To empty the cryostat.

This requires the cryostat to be pressurised by helium or nitrogen gas to blow the liquid out through the vent line. The position of the valves is shown in the table. The opening of the gas valve, V6 will be determined by the rate of removal of the LN2 which should ideally be in 2-3 minutes. Once the LN2 has been removed from the cryostat (as indicated by a level monitor) and from the vent line (as indicated by ?), the gas can be shut off (close V6).

Valve	Position
V1	open
V2	closed
V3	open
V4	closed
V5	open
V6	control open

2.1.3. Filling the cryostat after a magnet pulse

The magnet is expected to rise from ~80 K to 110 K during the magnet operation. It is necessary to cool the magnet in ~30 minutes to ~80 K. The position of the valves is shown in the table.

Valve	Position
V1	open
V2	control open
V3	closed
V4	open
V5	open
V6	closed

2.1.4. Overnight.

The cryostat can be allowed to warm up to ~100 K overnight to remove any traces of oxygen. The valves would be as shown in the table.

Valve	Position
V1	open
V2	closed
V3	open
V4	open
V5	open
V6	closed

2.1.4. The bypass and testing

The system can be partially tested without the cryostat by flowing LN2 through the bypass line in the valve box and out through the vent line.

2.2. Dimensions of the lines

The length of the lines is assumed to be 80 m from the LN2 storage vessel and the vent line outlet to the cryostat, via the valve box. The lines are assumed to be smooth bore pipe except for the 20 m vertical drop from the ground level to the experiment level, where the lines will be corrugated.

The magnet gains energy, E = 22 MJ during the current pulse. If this energy is removed by the latent heat, L = 196 J g^{-1}, of the LN2 only, then the volume of LN2 is,

$$V = \frac{E}{\rho L} = 140\,\text{litres} \tag{1}$$

where the density of LN2, ρ = 810 g l^{-1}. This volume of LN2 must pass through the line in 30 minutes or less, i.e. an average minimum flow rate of 4.7 l min^{-1} or 3780 g min^{-1} (= 63 g s^{-1}). Peter Titus has usually assumed a flow rate of 200 g s^{-1}, so this figure is taken for the calculation. If the pipe bore is d = 10 mm, then the velocity, v, of the LN2 at 200 g s^{-1} is 3.1 m s^{-1}. The Reynolds number is [1],

$$R = \frac{dv\rho}{\mu} = 160 \tag{2}$$

where the dynamic viscosity, μ = 1.59x10^{-4} Pa s. With this Reynolds number the flow is laminar. The pressure drop across a smooth bore pipe of length l = 100 m is [1],

$$p = 32000\frac{\mu v l}{d^2} = 0.16\,\text{bar} \tag{3}$$

Clearly a pressure of ~1 bar will be adequate to drive the LN2 into the cryostat in the time.

The gas evolved in cooling the magnet corresponds to a flow rate of W = 720 kg hr^{-1}. If the vent pipe bore diameter is D = 75 mm, then the Reynolds number is [1],

$$R_g = 354\frac{W}{D\mu_g} = 9.3\cdot 10^5 \qquad (4)$$

where the dynamic viscosity of the gas is, μ_g = 5.5x10^{-3} centipoise. From Crane [1] we find the friction factor f = 0.019 and the pressure drop across 100 m of pipe is,

$$P_g = 62530\frac{fW^2}{D^5\rho_g} = 0.06\,\text{bar} \qquad (5)$$

where ρ_g = 4.69 kg m^{-3}.

To remove 300 l of LN2 from the cryostat in 2 minutes through the vent line of 75 mm bore diameter will require a velocity of 56.6 cm s^{-1}, giving a Reynolds number of 216 (equation 2) and a pressure drop of 0.03 bar (equation 3) across 100 m of pipe.

Table 1 Summarises the pressure drops in the inlet and vent pipes. The pressures are very low and the inclusion of 20 m of corrugated pipe and bends will increase these values towards 1 bar. It is not worth calculating to any greater precision at present since the number of bends and their radius is unknown. These pressure drops ignore the head heights. The pressure due to 20 m of LN2 is 1.6 bar. Therefore, there is an additional 1.6 bar forcing the liquid into the cryostat from the storage vessel and an additional 1.6 bar is needed to force the LN2 from the cryostat out of the vent line.

Table 1. Pressure drops in the pipes, ignoring head pressures.

Operation	**Inlet pipe** 10 mm bore dia bar	**Vent pipe** 75 mm bore dia bar
Filling the cryostat	0.16	0.06
Emptying the cryostat	-	0.03

Note that the volume of the vent line is 350 l. This is more than the volume of LN2 (300 l) in the cryostat.

2.3. Costs

The costs for RAL to design, supply, install, commission and operate the cryogenic system is shown in Appendix 2. Costs include manpower. It assumes that the LN2 storage vessel is supplied by CERN.

3.0 Returning the LN2 into the storage vessel

Figure 2 shows the scheme for returning the LN2 into the storage vessel before operating the pulsed magnet.

In this scheme the 300 l of LN2 is driven from the cryostat into the storage vessel and not vented to the atmosphere. It was considered that this was an unusual operation for the storage vessel and might give problems. However, this is basically the routine method of filling the vessel by the LN2 supplier. I am at present in discussion with Air Products on the viability of the scheme. The advantages are cost and simplicity - there are only 2 valves in the valve box and the fill and empty lines are combined in one 3 inch bore diameter pipe and the vent can be relatively small.

The bypass line is avoided and if operation of the system is required without the cryostat, then it is relatively simple to connect a small length of insulated line between the fill/empty connection and the vent.

In addition, the vent line and valve V2 could be removed from the cold box and be relatively "warm".

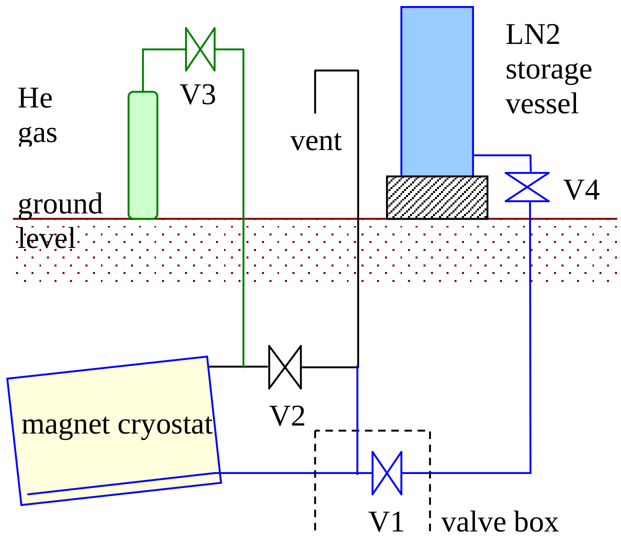

Figure 2. A simple system with LN2 returning to the storage vessel.

4.0 Emptying the cryostat. Removal of the liquid in the vent line.

The cryostat is to be emptied by pressurising the cryostat with nitrogen or helium gas. This works while there is a horizontal surface and the gas pressure is applied from above – see figure 3.

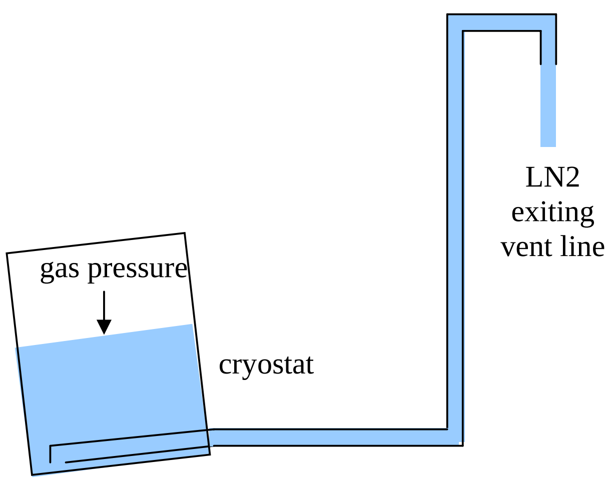

Figure 3a. Removal of LN2 from the cryostat.

However, when the liquid is in a vertical or horizontal pipe the liquid will not be displaced, but bubbles of gas will flow through the liquid, see Figures 4a and 4b.

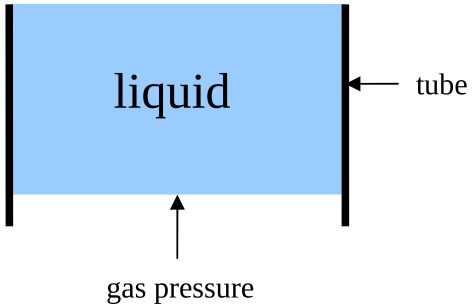

Figure 4a.

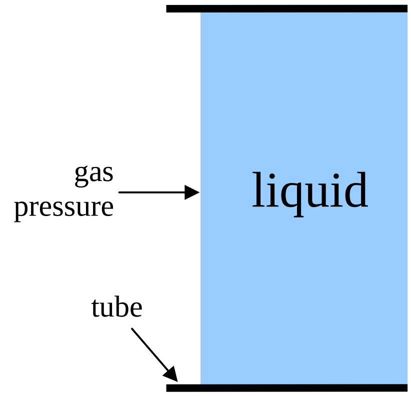

Figure 4b.

Gas pressure applied to the base of a long vertical or horizontal pipe of large diameter, compared to the diameter that the liquid can support a meniscus. The gas will bubble through the liquid.

Thus, when the surface of LN2 in the cryostat dips below the level of the entrance to the discharge pipe at the bottom of the cryostat, little liquid will be forced out of the pipe, although bubbles passing through the pipe could displace some of the liquid through the vent line. It is interesting to note that the volume of the vent line is almost the same as the volume of the cryostat – 300 l. Thus very little LN2 will be vented onto the ground but will be displaced into the vent pipe. When refilling the cryostat after activating the magnet the LN2 in the vent line may well be blown out by the large flow of gas that is boiled off in the magnet cooling cycle.

Thus, apart from a small quantity of LN2 remaining in the cryostat there will be LN2 in the vent line. This will be activated when the beam hits the mercury jet. To overcome this problem it is suggested that the line be tilted down after emerging from the cryostat, as shown in Figure 5. This will enable a surface to form on which the gas pressure can bear downwards and expel most of the air in the horizontal section of the vent pipe. Some small amount of LN2 will always be left in the bottom of the cryostat – unless the vent pipe was to be repositioned at the lowest point beneath the cryostat. Also, it is not clear how much of the LN2 will be displaced from the upward-tilting vent line within the cryostat.

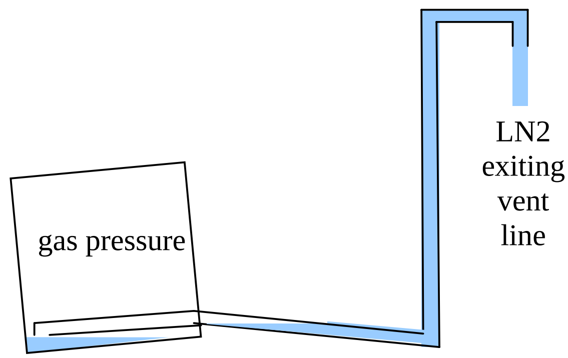

Figure 5. Emptying the horizontal section of the vent line near the cryostat.

5. Is it necessary to remove the LN2 from the cryostat?

I believe that it is not necessary to remove the LN2 from the cryostat between beam pulses. The activation will not be a problem when vented to the air. This simplifies the cryogenic system still further, as shown in Figure 5. Marco Silari and I am looking into this.

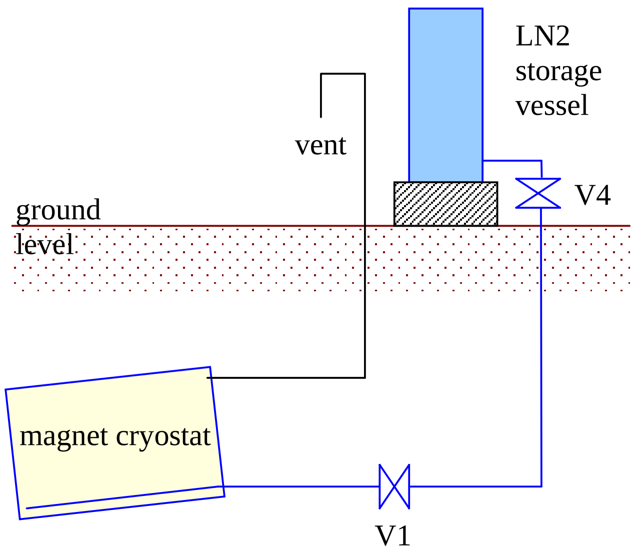

Figure 5. Simple cryogenic system – if emptying the cryostat between pulses is not required.

6. Accumulation of oxygen

Any oxygen dissolved in the LN2 can be transformed into ozone by ionising radiations. The ozone can rapidly decompose causing an explosion [2]. It is unlikely that oxygen will accumulate in the cryostat since the LN2 is constantly being evaporated and replenished during the experiment. Also, it is planned to let the cryostat warm up to ~100 K every night, thus evaporating the oxygen.

Another possible place for accumulation of oxygen is voids between the closure plate on the cryostat and the foam insulation. Air can condense in these voids, or possibly in the voids in the foam itself, forming a potential hazard.

7. Control and monitoring system

The control system is quite simple. All valves are on/off except for V2 (Figure 1) which can control the flow of LN2 into the cryostat during the fill cycles. All valves are remotely operable.

Personally, I would have a manual control for the system since I do not believe that it warrants the expenditure of computer logic system. All valves would be operated from switches in the control room for the experiment. The degree of opening of the control valve, V2, would be via a rotating knob, whose angular position was proportional to flow.

There are to be a LN2 level meter, and a back-up level resistor positioned at the bottom of the cryostat to indicate when the level reaches the entry of the sloping vent/fill pipe. In addition there will be several temperature monitors attached to the magnet coils.

References

[1] Crane, Flow of Fluids through Valves, Fittings and Pipe, Crane Ltd, 11-12 Bouverie Street, London EC4Y 8AH, Technical Paper No. 410M, 1983.

[2] C. R. Gregory, C. W. Nuttall, CERN-AT-95-06.

J R J Bennett

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Appendix 1

Present at the meeting

Roger Bennett, RAL	Part time:
Friedrich Haug, CERN	Harold Kirk, BNL
Yury Ivanyushenkov, RAL	Kirk McDonald, Princeton

F. Haug, CERN, 9.11.2004

DRAFT SUMMARY ON CRYOGENICS FOLLOWING THE MERCURY TARGET MEETING 4/5. 11. 2004 AT CERN

CRYOGENIC INFRASTRUCTURE

POWER SUPPLY capacity does not require sub-cooling. Magnet operation temperature at 82 K of magnet with approximately 78 K of LN2 bath.

CONSEQUENCES FOR CRYO
No sub-cooling required, i.e.
-NO VACUUM PUMP to reduce pressure on LN2 bath which can be omitted leading to simplification of system
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FURTHER SIMPLIFICATIONS
(flow scheme F. Haug presented 4.11.04):
PROPOSAL TO DO
-WITHOUT WARM EXHAUST (VENT)
Which eliminates also the need for
-ELECTRICAL OR PASSIVE HEATER
i.e. further simplification and cost reduction

This means Operation simply with LN2 supply from an external dewar at surface and cold gas or LN2 return to the surface.
For this either two separate transfer lines or a so-called one “two-in-one” is used.

TRANSFER LINES

The transfer lines are of the flexible ones “KABELMETAL” or similar permitting quick and easy installation for this temporary experiment.

VALVE BOX

“Concentration” of instrumentation for “external cryogenic” in one valve box at proximity to magnet.
The current flow scheme (P. Titus et.all) foresees four (4) cold valves in the valve box

CONTROL VALVES

-Five cold valves. V1 on LN2 dewar, V2, V3, V4, V5 in valve box.
-One warm valve V6

CRYOGENIC EQUIPMENT INVENTORY AT CERN AND AVAILABILITY

F. Haug investigates on the potential use of existing equipment at CERN
-Several “two-in-one” identical transfer lines of former LEP exist

-A 6000 liter dewar, (+ alternatives)
-valve box envelopes, valves ???

Further investigations are being persued…..

SURFACE INFRASTRUCTURE
-Concrete platform for Equipment installation at surface
(site committee permission) for LN2 dewar and Nitrogen gas or Helium bottles (200 bar)

RADIATION SAFETY ISSUES
a) Drill whole in concrete blocks for installation of short transfer lines (low cost) between valve box and magnet
b) Residual LN2 quantity of 1 to 2 liters

In both cases preliminary answer of Thomas Otto (9.11.04) = positive. However, final answer only after simulation calculations in Jan. 2005.

MAGNET AND CRYOSTAT
-Decrease cryostat void volume from 300 l to less than 100 liters using “fillers” of appropriate material. (Reduces filling and emptying time and LN2 loss)
-Add “descrete” level sensor at bottom of cryostat to detect minimum level
-Mechanical interfaces to external cryogenics

PROCESS CONTROL SYSTEM
Cryogenic process must be fully automized without requiring operator or engineer interventions during normal running !
Open issue remains on the type of control system. However, “Unicos” is the prefered CERN standard. ECR group could give full assistance.

PRE-COMMISSIONING
The external system can be fully commissioned without magnet and all functional tests can be made.

BASIC OPERATION PRINCIPLES
-Cooling, filling and emptying is done via the drain port.
-Exhaust is at top port
-pressurisation for emptying with N2 or He 200 bar bottles
-Exhaust only to ambient, no N2 recovery

1. Initial Cool down (so far identical with 2.)
Open: V1,V2,V5,V4
2. Cool down after pulse
Open: V1,V2,V5,V4
3. Emptying
Open: V6, V5, V3
4. Stanby mode
Open: V4

Appendix 2. Cost of supplying the cryogenic system as shown in Figure 1.

Cost of Cryogenic System	FY2005/06		FY2006/07		FY2007/08		Total
	Staff months	£k	Staff months	£k	Staff months	£k	£k
Hardware, including design and testing							
Valve box with 3 open/closed valves and 1 control valve		42.0					
Transfer line ID25, 30 m rigid, 20 m flexible		15.0					
Transfer line ID75, 30 m rigid, 20 m flexible		30.0					
Transfer line ID25, 10 m		2.5					
Transfer line ID75, 10 m		4.0					
Helium line ID25, 60 m		2.0					
Additional equipment (Dewar etc.)		10.0					
Sub-total:		*105.5*					
Transportation to CERN		2.0					
Installation at CERN		40.0					
Controls							
Components		15.0					
Software		10.0					
Total Hardware and Control Systems		**174.5**		**0.0**		**0.0**	**174.5**
VAT		**30.5**		**0.0**		**0.0**	**30.5**
Travel and Subsistence		**15.0**		**3.0**		**10.0**	**28.0**
Staff (at £6.5 k/month)							
Cryogenics scientist, TW Bradshaw	0.5	3.3			0.3	1.6	
Cryogenics engineer, Y Ivanyushenkov							
Design	2.0	13.0					
Manufacturing	0.5	3.3					
Installation	0.5	3.3					
Comissioning	0.5	3.3			0.5	3.3	
Experiment					1.0	6.5	
Mechanical enginee, MJ Mills							
Design	1.0	6.5					
Manufacturing	0.3	1.6					
Instrumentation engineer, MJD Courthold							
Design	2.0	13.0					
Comissioning	1.0	6.5					
Other CCLRC staff:							
Physicist, J.R.J.Bennett	1.5	9.8	0.5	3.3	1.0	6.5	
Total staff	**9.8**	**63.4**	**0.5**	**3.3**	**2.8**	**17.9**	**84.5**
Grand Total Cost		**283.4**		**6.3**		**27.9**	**317.5**