Requirements for the Cryogenic System for the 15-T Pulsed Solenoid Magnet

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1 Basic Requirements

We desire a liquid-nitrogen cryogenic system for the 15-T pulsed solenoid magnet for the CERN High Power Target experiment [1].

The basic requirements are twofold:

1. Provide cooling from room temperature to 70K at the beginning of each block of running. This part of the cooling cycle can be "slow".
2. Provide cooling "as quickly as possible" from $\approx$ 100K back to 70K after each pulse of the magnet to 15-T. The desired time for this part of the cooling cycle at most 30 min.

2 Elaborations

We now elaborate on these requirements.

1. The requirement of a temperature of 70K at the end of a cooling cycle implies that the magnet must be at a vacuum of about 0.1 atm during the latter part of the cycle.

   The magnet vessel is rated for 15 atm.

2. As shown in Fig. 1 (Fig. 21 of [1]), the heat load of one beam pulse is about 25 MJ, which causes a 30K rise in the magnet temperature. It will require about 100 l of liquid nitrogen to remove this 25 MJ, assuming that all of the latent heat of vaporization of that liquid is used for cooling.

   Similarly, the initial cooling of the magnet from 300K to 70K will require about 1000 l of liquid nitrogen, if used effectively.

3. A special requirement is that there be no liquid nitrogen in the magnet when it is energized for use with a proton beam pulse. This is to avoid activation of the nitrogen by the proton beam, which would then lead to issues of disposal of radioactive material. Thus, a cooling cycle to 70K is not complete until the liquid nitrogen is removed from the magnet. And, we desire no liquid nitrogen in the feed line inside the beam tunnel. Likewise, there can be no liquid nitrogen storage tank inside the beam tunnel.

   It is desirable, but a requirement, that the magnet be under vacuum when pulsed, to avoid activation of nitrogen gas.

   Figures 2 and 3 (Figs. 38 and 39 of [1] sketch the expected configuration of the experiment in the CERN TT2A tunnel. The last valve in the liquid nitrogen feed line must

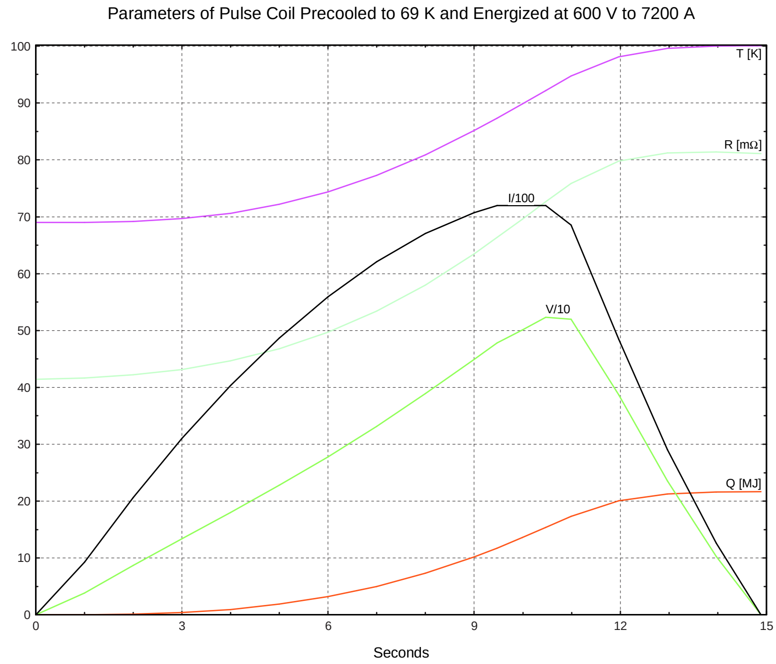

Figure 1: Time dependence in the 15-T pulsed magnet of the temperature T, the current I (with is directly proportional to the magnetic field B), the coil resistance R, the voltage drop V across the coil, and the energy Q deposited in the coil by Joule heating.

be some 10 m from the magnet (unless we drill a hole for the line through the wall separating the TT2A and TT2 tunnels), to avoid activation of liquid nitrogen.

4. The requirement that there be no nitrogen in the magnet at the end of a cooling cycle, combined with the requirement of a cooling cycle of 30 min or less, has led us to prefer (not require) a cryogenic system in which the magnet attains 70K with nearly zero liquid nitrogen left inside the magnet.

5. The 15-T solenoid magnet is sketched in Fig. 4. All of the magnet leads and piping pass through one end of the magnet, with the exception of a drain on the bottom center of the out vacuum vessel, not shown in Fig. 4 but shown in Fig. 5.

   The flow of liquid nitrogen within the magnet is sketched in Fig. 6. The liquid enters through a port near the top of the endplate of the magnet, and passes across the top of the magnet to an input plenum at the other end.

   The liquid can then pass into the 4 concentric rings of cooling channels around and between the 3 magnet coils. These channels have a total volume of about 10 l. I believe that a set of circumferential grooves is being added such that once the liquid (or gas) has entered one ring of channels, it can flow both horizontally (along the channels) and azimuthally (around the grooves).

   The liquid (and gas) exits the magnet coils into a plenum on the inside of the magnet endplate. Gas can then exit the magnet through an outlet port, located just below

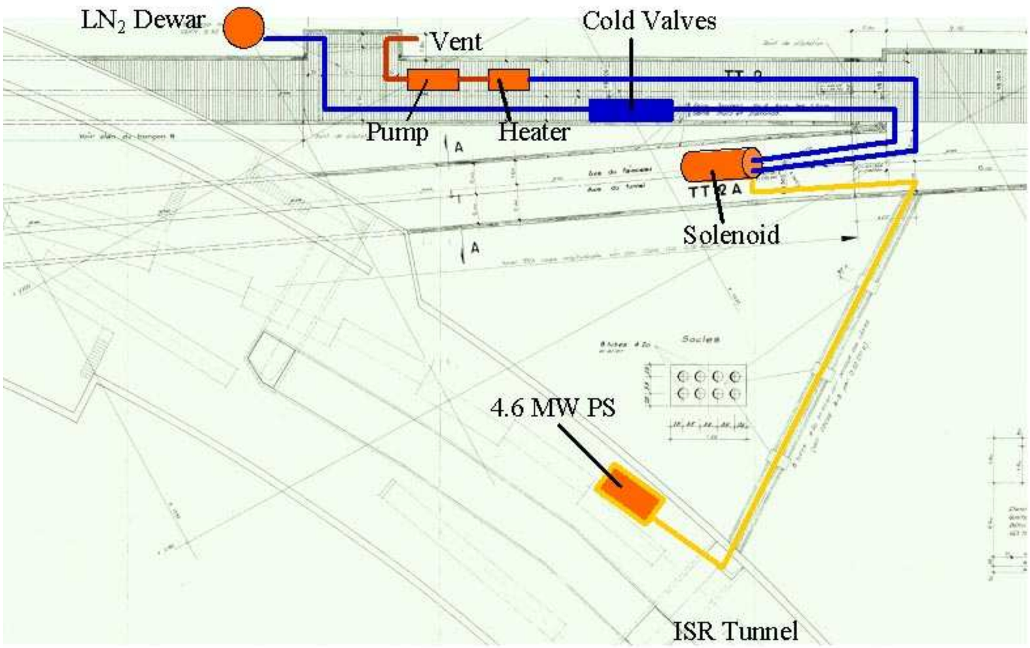

Figure 2: Plan view of a possible arrangement of DC power lines and the cryogenic transfers, with the solenoid magnet at the location of option 2. The 4.6 MW power converter could reside in the ISR tunnel, with the DC bussing passing through an existing 2-m high horizontal access shaft to the TT2A tunnel. The cryogenic transfer lines would pass along the TT2 tunnel and up the vertical access shaft to 6,000 l dewar on the surface.

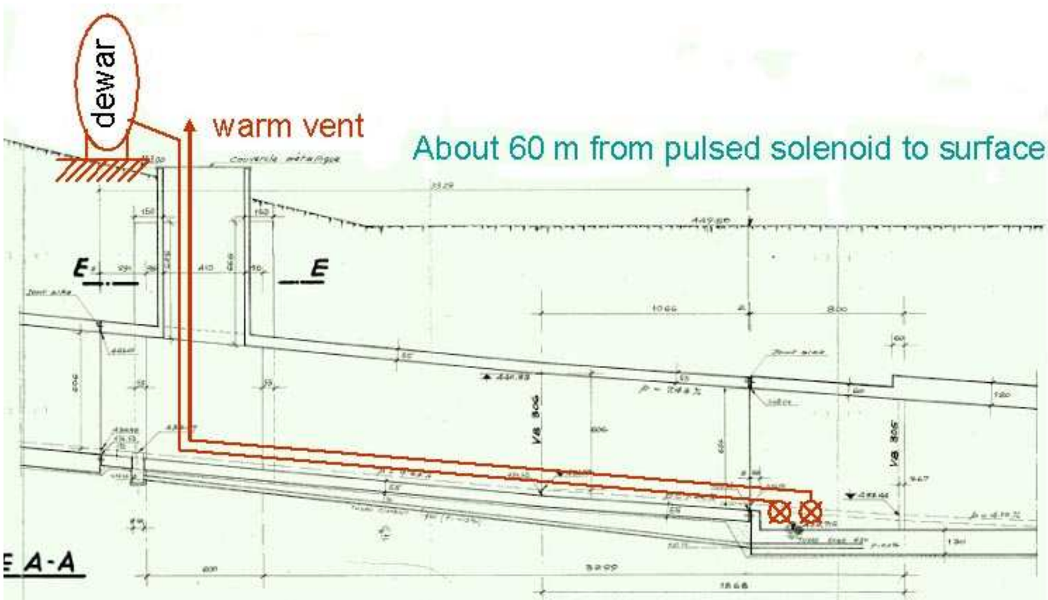

Figure 3: Elevation view of the sloping TT2 tunnel and the associated vertical access shaft. The cryogenic transfer lines are shown for option 1.

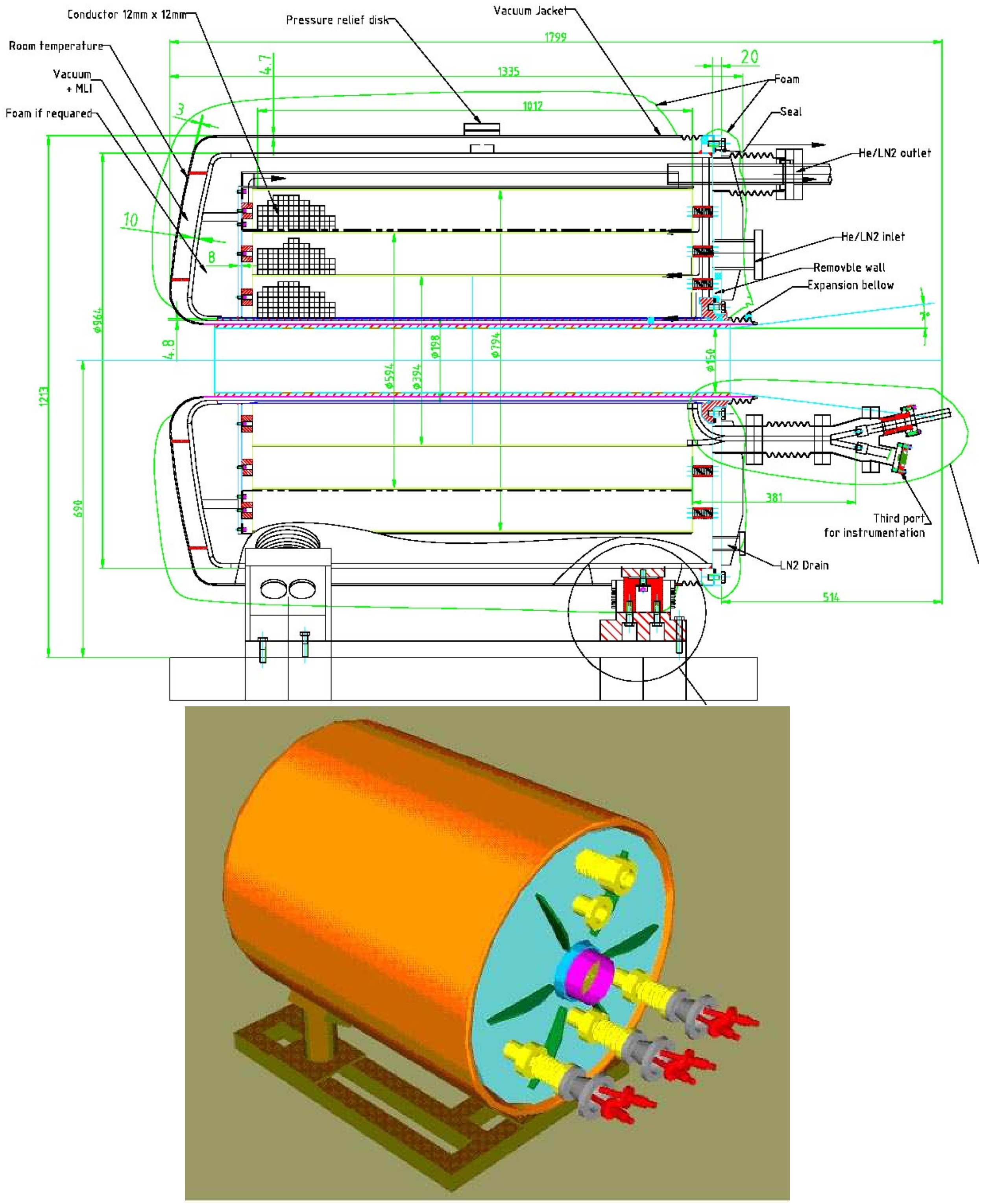

Figure 4: Sketches of the concept of a 15-T, pulsed copper solenoid for use in the prototype target studies [2].

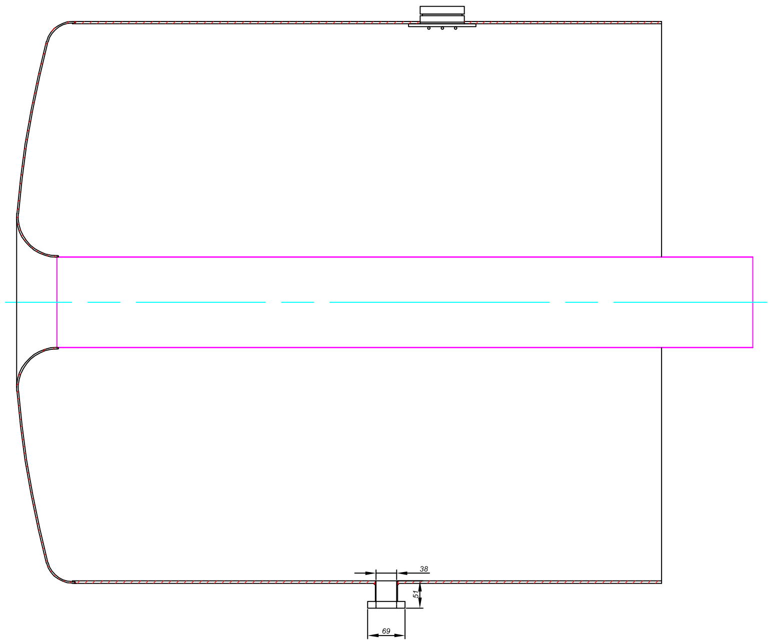

Figure 5: Vertical section through the outer vacuum vessel of the magnet, showing the drain port at the bottom. From drawing bnl-011.dwg, available at http://www.psfc.mit.edu/people/titus

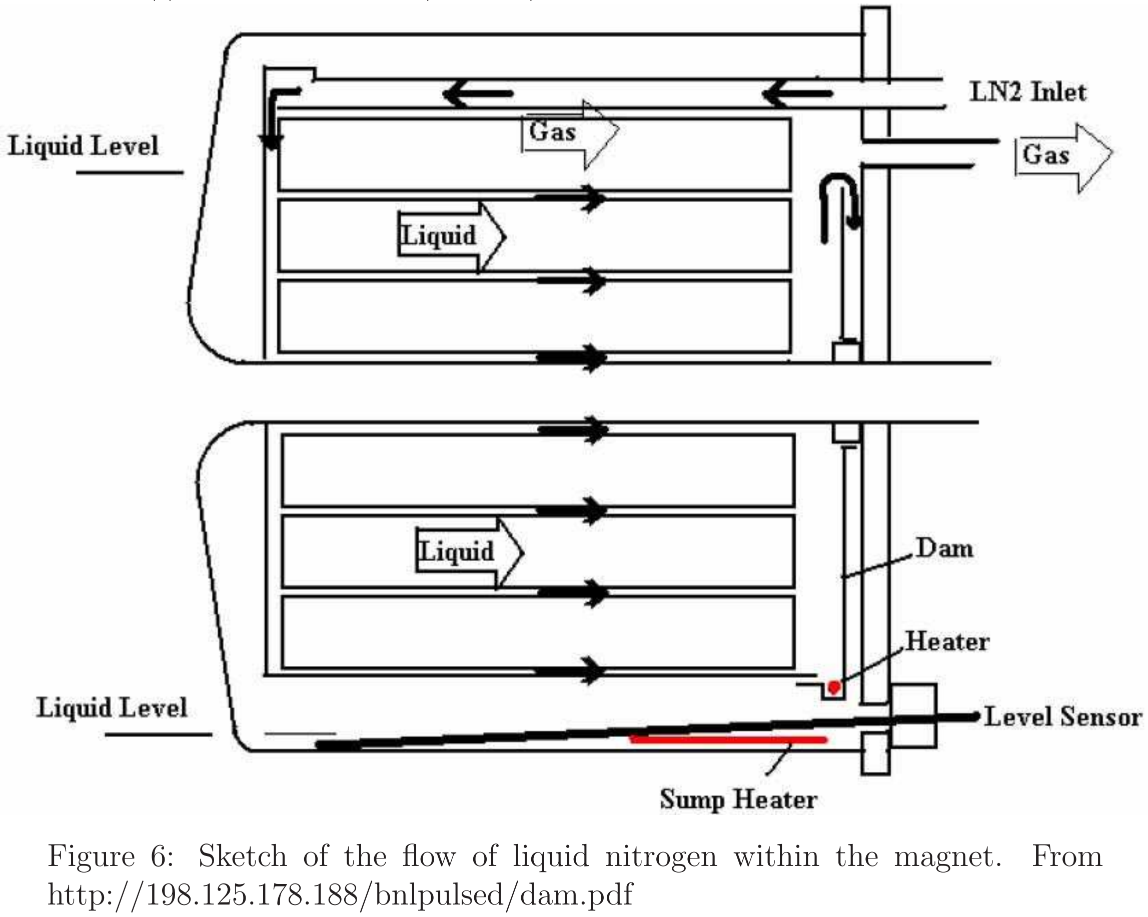

Figure 6: Sketch of the flow of liquid nitrogen within the magnet. From http://198.125.178.188/bnlpulsed/dam.pdf

the inlet port. It is not expected that liquid will be taken out of this port. Rather, if liquid is to be removed from the magnet, it will pass out through the drain port shown in Fig. 5.

The magnet can be filled with a total of about 300 l of liquid (which is 3 times as much as is actually needed to cool the magnet from 100 to 70 K)

6. A difficulty with this flow scheme (which was adopted at a time when it was thought that the coolant would be He gas [3]) is that the inner of the 3 magnet coils would receive no liquid into its channels unless the liquid level inside the magnet is more than 30 cm high. This means that the magnet would have to be filled with much more liquid than needed, in principle, to cool from 100 to 70K if there is to be any cooling of the inner coil.

7. A possible solution to minimize the amount of liquid left in the magnet at the end of a cooling cycle is to install a "dam" at the output end of the cooling channels, as shown in Fig. 6.

   The liquid level inside the magnet would be controlled such that no liquid ever spills over the dam. In this case, the drain port at the bottom of the magnet would not be used. However, when the magnet reaches 70 K there would still be about 10 l of liquid "trapped" behind the dam. This liquid would have to be boiled away by a heater. Since it takes about 2.5 MJ of energy to vaporize 10 l of liquid nitrogen, this would require, say, a 2.5 kW heater to be operated for 1000 s = 15 min = half the desired time of the cooling cycle.

   A sketch of a minimal cryogenic system for use with the dam is shown in Fig. 7. Liquid nitrogen is supplied from a storage dewar (on the surface outside the tunnels) and enters the magnet through a proportional control value. This valve is to be programmed to minimize the amount of liquid in the magnet when it reaches 70K (while maintaining a cooling time of less than 30 min). To achieve a final temperature of 70K, the magnet must be at partial vacuum. The vacuum pump is at room temperature, so there must be a heater between the magnet and the pump to warm the gas.

8. Earlier designs of cryogenic schemes that utilized the drain valve appeared to be considerably more costly because of additional components needed to handle the liquid that is drained from the magnet. However, we should reconsider this option.

   Some recent thoughts on a scheme that utilizes the drain are represented in Fig. 8 by F. Haug of CERN.

9. We would like to test the magnet at full power with a near-final cryogenic system before we take beam at CERN. Because the 5 MW power supply is a costly, long-leadtime device, we may not be able to perform this test at CERN. An option exists to perform the cryo test at MIT, where a 10 MW supply is available for short-term use. Thus, we may have the additional requirement that the cryogenic system be implementable first at a site other than CERN, while remaining compatible with CERN cryogenic operation and safety standards.

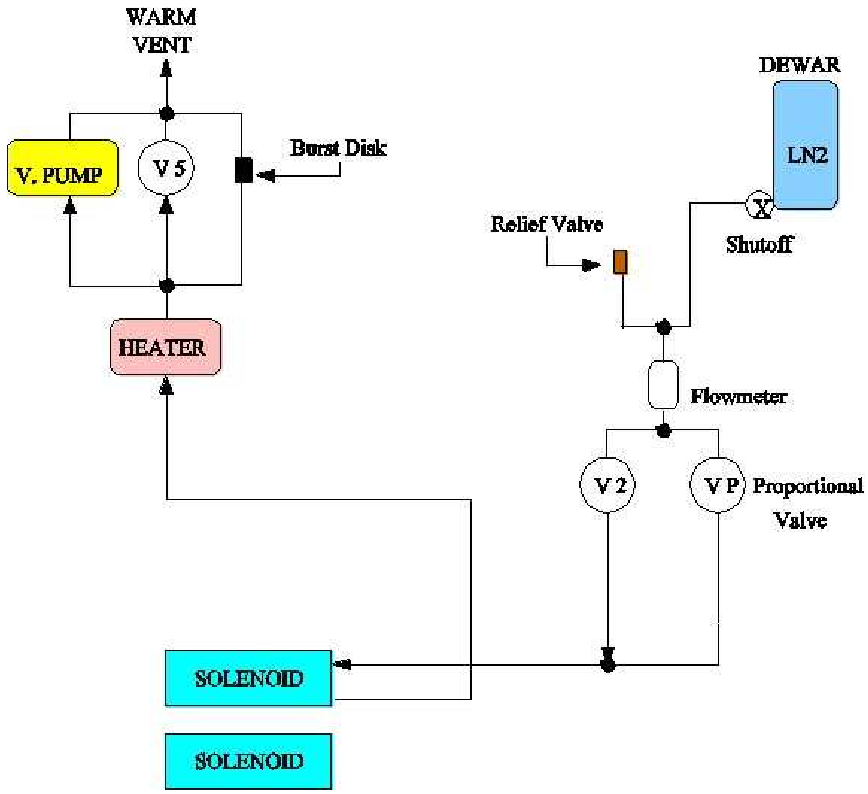

Figure 7: Sketch of a cryogenic system for operation of the magnet with an internal dam for the liquid nitrogen.

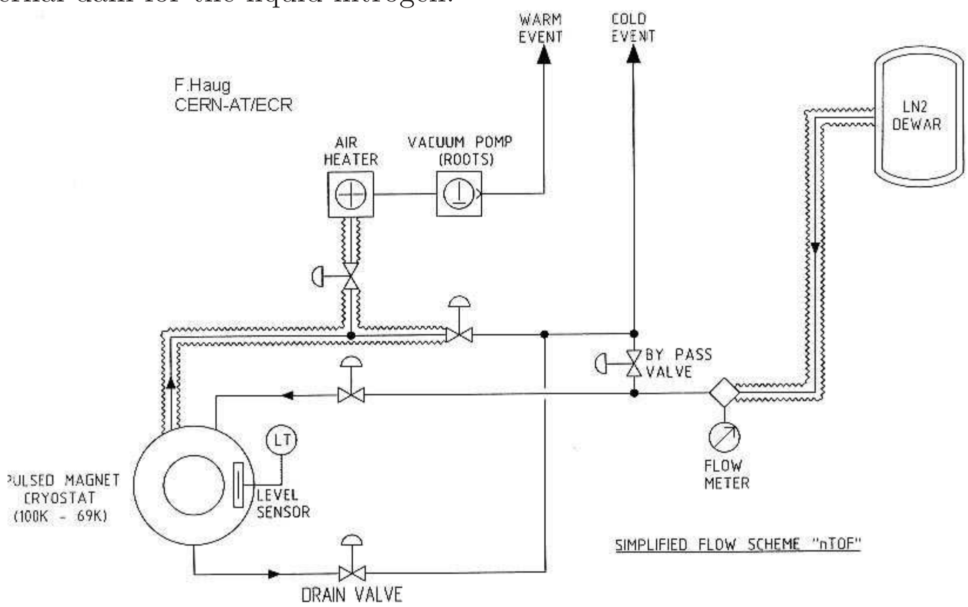

Figure 8: Sketch of a cryogenic system for operation of the magnet that uses the drain (F. Haug).

3 References

[1] R.J.R. Bennett *et al.*, *Studies of a Target System for a 4-MW, 24-GeV Proton Beam*, submitted to the CERN INTC (April 26, 2004), http://www.hep.princeton.edu/~mcdonald/mumu/target/cern_proposal.pdf

[2] P. Titus, *15-T Pulsed Magnet for Mercury Target Development* (Sep 1, 2004), http://198.125.178.188/bnlpulsed/ornl2004.pdf

[3] G.T. Mulholland, *Cryogenics for the Pulsed Solenoid Magnet* (Sept. 6, 2002), http://www.hep.princeton.edu/~mcdonald/mumu/target/mulholland/E951_ESR_Pres_090602.pdf *E-951 Cryogenic Operating Procedures* (Sept. 20, 2002), http://www.hep.princeton.edu/~mcdonald/mumu/target/mulholland/E951_Operating_ProceduresB.pdf