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Switzerland

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Engineering Specification

D1 (LBX) – DIPOLE COOLING SCHEME

Abstract

Superconducting beam separation dipoles of four different types are required in the Experimental Insertions (IR 1, 2, 5, and 8) and the RF Insertion (IR 4). The D1 single aperture dipoles are among those utilized in the Experimental Insertions to bring the beams into collision. The superconducting D1 dipoles (LBX) utilized in the low-luminosity insertions at IR 2 and IR8 are cooled at 1.9 K. This specification establishes the requirements and interfaces for the cooling of the LBX dipoles.

Prepared by :	***Reviewed by :***	***Approved by :***
K. C. Wu BNL Kcwu@bnl.gov	**E. Willen** BNL Willen@bnl.gov **J. Strait** FNAL strait@fnal.gov	**Thomas TAYLOR** LHC/DLO

Approval Group Members:

Ian COLLINS, Claude HAUVILLER, Jim KERBY, Tadeusz KURTYKA, Ranko OSTOJIC, Vittorio PARMA, Philip PFUND, Steve PLATE, Jean-Pierre QUESNEL, Roberto SABAN, Blazej SKOCZEN, Pierre STRUBIN, Thomas TAYLOR, Jean-Philippe TOCK, Gilbert TRINQUART, Rob VAN WEELDEREN

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1.0	2001-02-05	All	Initial submission
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		4, 7	Editorial changes
		5	Helium II bath pressure changed from 1 bar to 1.3 bar.
		7, 8, 9	Tables 1, 2, and 3 heat loads updated to agree with [4] and reflect static jumper and QRL loads allocated to DFBX and higher heat loads due to photoelectron effects consistent with February 2001 update to reference [4]
1.1	2001-05-03		First released version

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1. OVERVIEW

Each superconducting D1 dipole cryo-assembly (LBX) will be a single aperture, RHIC-type cold mass in a cryostat [1,2,3]. The D1 and D2 magnets bring the two beams of the LHC, separated by 194 mm in the arcs, into collision at four separate points, then separate the beams again beyond the collision point. The D2 magnets are specified for IRs 1, 2, 5 and 8. Superconducting D1 magnets will be used on each side of IPs 2 and 8. For IPs 1 and 5, warm D1 magnets (MBXW) are planned. This specification refers only to the superconducting LBX cryo-assemblies. One side of one such region is shown in Figure 1.

1.1 LOCATION

The configurations of the four LBX cryo-assemblies in the LHC are similar but not identical. The differences are a result of variations in tunnel slope direction. In order to be able to have one spare replace any of the D1 magnet assemblies, differences between the magnets must be slight and easily accommodated by minor modifications to the spare. This is accomplished through the use of some redundant piping within the cryostat and by specific field-added components added to the spare by CERN prior to installation. In addition, some of the magnet assemblies manufactured at BNL will require minor modifications and specific field-added components depending upon the installation location. Using this approach allows the manufacture of five identical D1 units.

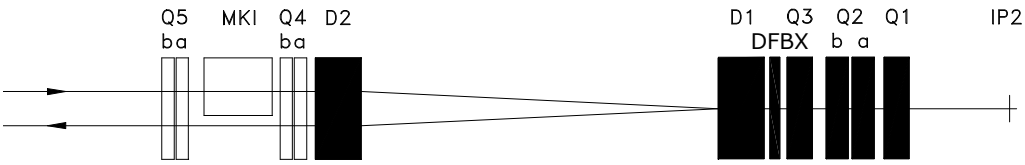


Figure 1. Geometry in Intersection Region 2 of the LHC. Dipole magnets D1 and D2 bring the beams into collision at IP2.

1.2 COOLING

The MBX magnets (LBX cryo-assemblies) are to be installed as D1 magnets in the LHC high luminosity interaction regions (IR2 and IR8) where, when LHC is operated with ultimate beam current intensity, a beam induced heating of one to two watts per meter is expected. To ensure proper cooling through the 1-mm channel between the coil and the beam tube, the D1 magnets are cooled by helium II at 1.9 K.

The cooling scheme for the LBX is similar to that of the LHC arc magnets, in which a heat exchanger tube is used to provide cooling to the magnet coil via a bath of helium II at 1.3 bar. The heat exchanger tube is connected to the LHC cryogenic distribution Header B. The pressure is nominally kept at 0.016 bar but can reach 0.019 bar depending upon location and machine operating mode. The liquid and vapor phases of helium inside the exchanger tube must flow in the same direction (always downward) to avoid flow instabilities.

Four 30 mm diameter cooling holes are included in the iron laminations of the RHIC-type MBX yoke. See Figure 2. The upper two holes will accommodate 28.6 mm

diameter copper tubes, which are approximately half the size of those used in the LHC arc magnets. For the D1 configuration, the cooling capacity for each tube is approximately 1.4 W/m as calculated from pressure drop, liquid velocity and heat exchanger area. Two tubes will be installed in each D1, providing 28 W of cooling.

Beam Screens are needed to shield the dynamic heat load. The beam screen will be provided and installed by CERN.

2. CRYOSTAT LAYOUT

The cross section of the LBX cryo-assembly is given in Figure 2. The D1 magnet, enclosed in an aluminum heat shield, is supported by three Ultem posts. There are eight cold pipes, identified as CL/LD, C', CY, E1, E2, X and XB. The functions of the pipes are discussed below. Complete pipe sizes and locations are detailed in the LBX Interface Specification[3].

- CL/LD is a single pipe that serves two different functions depending on whether the magnet is installed in the left or the right side of the IR. In the left side of the IR, the line is identified as CL and is used as the 4.5 K cooldown supply. In the right side of the IR, this line is identified as LD and is used as the quench relief and cooldown return. The inner diameter of CL/LD line is 68.8 mm (2.71 inch).
- C' is a small line for the 4.5 K beam screen supply. The inner diameter of C' is 13 mm.
- CY is the 1.9 K liquid supply line. The inner diameter of CY is 10.2 mm (0.40 inch).
- E1 and E2 are used to cool the heat shield at 50 K. The inner diameter of the shield supply line (attached to the heat shield) is 54.8 mm (2.16 inch). The inner diameter of the shield return line (on supporting bracket) is 68.8 mm (2.71 inch).
- X are the helium II heat exchangers. Their inner diameter is 24.5 mm (0.965 inch).
- XB is the 1.9 K vapor return. The inner diameter of the XB line is 68.8 mm (2.71 inch).

For the left side of the IR, CY will not be used. For the right side of the IR, XB will not be used. This cryostat layout allows interchange of magnets between the left and the right sides with minimum effort.

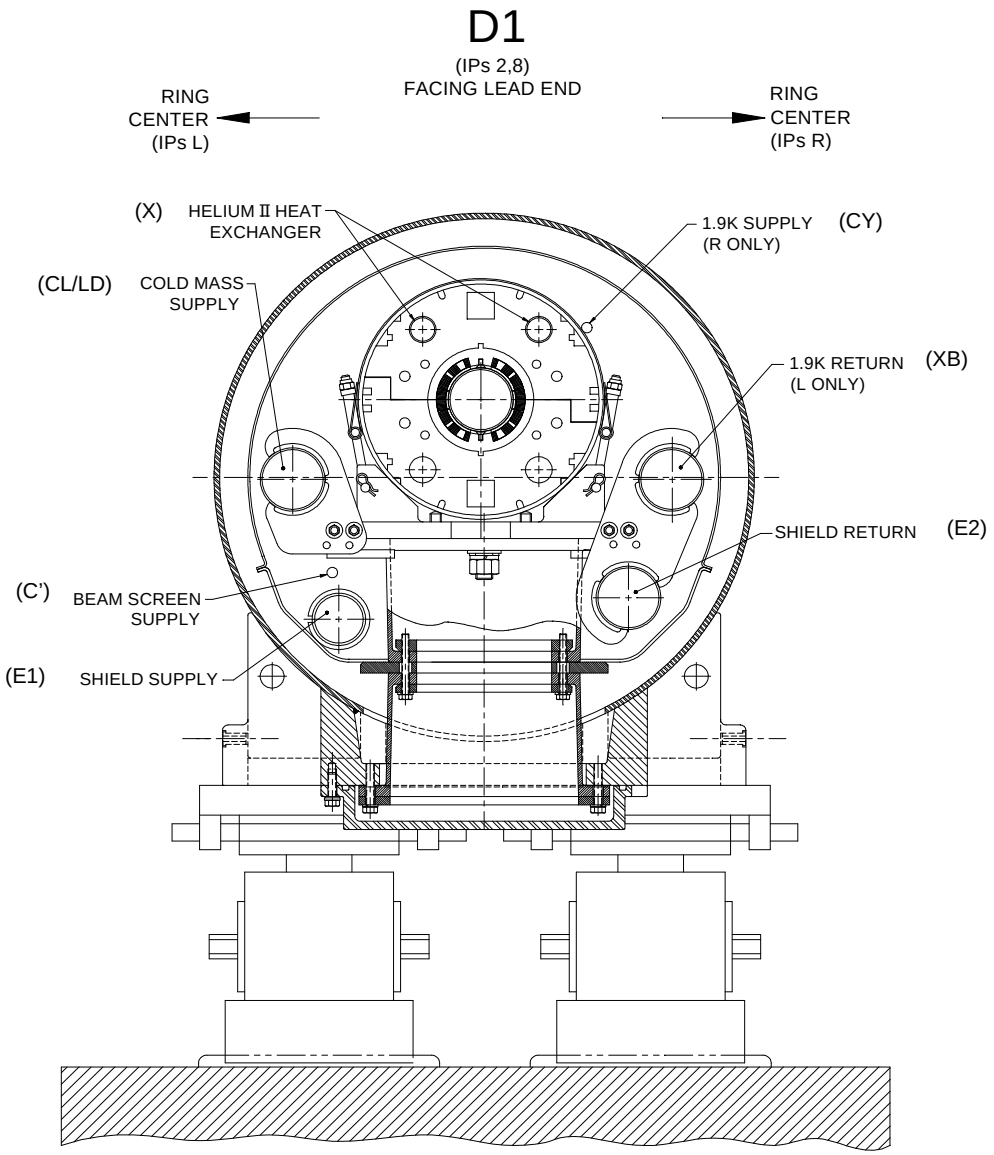


Figure 2. Sectional view of the LBX (D1) cryostat.

3. COOLING FLOW

3.1 GENERAL REQUIREMENTS

Heat load is a key parameter for a cooling system. In LHC, the heat loads consist of two types. The static heat load comes from conduction through the supports, and radiation past the thermal insulation of the cryostat. The dynamic heat load comes from machine operation. The dynamic heat load consists of synchrotron radiation, image currents, beam scattering and photoelectron effect. For the LHC operating condition, the dynamic heat load is large compared to that of the static heat load. The beam screen, operated between 4.5 and 20 K, is used to prevent a majority of the dynamic heat load from entering the 1.9 K magnet. There are three temperature levels of heat load for D1: 50-75 K of the thermal heat shield, 4.5-20 K of the beam screen and 1.9 K of the magnet cold mass.

Total static heat load of D1 is estimated by K. C. Wu and R. van Weelderen [4] based on the experience of RHIC and LHC. In Table 1, heat loads for electric splices, instrumentation feed through and cryogenic jumper lines are also included.

Table 1. Design Static Heat Load for D1 Magnet at IR2 and IR8. All units are in Watts.

Source	***Heat Shield***	***Beam Screen***	***Cold Mass***
	50-75 K	***4.5-20 K***	***1.9 K***
Supports	3.75	0	0.57
Thermal Shield	19.32	0	0
Radiation to cold mass	0	0	1.89
Resistive heating	0.01	0.022	0.28
Instrument feed	0	0	0.53
Cold to warm transition	13.00	0	2.78
QQS[a]	-	-	-
½ jumper[a]	-	-	-
Total	36.08	0.02	6.05

Note: (a) The function of the QQS and the jumper are served by the DFBX and these components of the heat load are accounted there[5].

The dynamic heat load is developed inside the beam tube. It has no effect on the 50-75 K heat shield. An actively cooled beam screen is designed to remove most of the dynamic heat loads that would otherwise be deposited in the magnet. Actively cooled beam screens will be used in the D1 magnets at both IR2 and IR8.

The dynamic heat loads of D1 at IR2 and IR8 shown in Table 2are taken from [4]; both the nominal and ultimate LHC operating conditions are given. The heat load for

synchrotron radiation, image current, beam scattering, and photoelectrons are given in watts per meter. The photoelectron heat input depends on whether or not the region has magnetic field. The length used in Table 2 is 10.23 meters and includes the interconnecting piping. The field free region is about 0.78 meter.

Table 2. Dynamic heat load with an active beam screen for D1 in IP2 and IP8 at nominal and ultimate operating conditions

Source	***Nominal***		***Ultimate***	
	Beam Screen 4.5 – 20 K	***Cold Mass 1.9 K***	***Beam Screen 4.5 – 20 K***	***Cold Mass 1.9 K***
Synchrotron radiation (W/m)	0.029	0	0.044	0
Image Current (W/m)	0.196	0.005	0.447	0.011
Beam gas scattering (W/m)	0	0.050	0	0.050
Photoelectron[a]				
-field region (W/m)	0.260	0	0.89	0
-field free region (W/m)	1.990	0	6.84	0
Secondaries (W/m)	0	0.010 (IP2) 0.145 (IP8)	0	0.010 (IP2) 0.145 (IP8)
Total for 10.23 meter length (W)	6.31	0.67 (IP2) 2.05 (IP8)	18.77	0.73 (IP2) 2.11 (IP8)

Note: (a) From the mechanical layout drawings [1], the field region is taken as the magnetic length 9.45m. The total length is taken as the cold mass length 10.23 m. Their difference is taken as the field free region 0.78 m.

Total heat load is the sum of static and dynamic heat load and is given in Table 3. The cooling system must be designed for the maximum heat load with a safety margin. Pressure and temperature at the 4.5 K supply line shall be 3 bar and 4.6 K. Pressure in the return line B and D is not expected to be greater than 0.019 bar and 1.3 bar respectively.

Table 3. Total heat load for each D1 magnet at IR2 and IR8 at nominal and ultimate operating conditions.

	Heat Shield	***Beam Screen***	***Cold Mass 1.9 K***	
	50-75 K	***4.5-20 K***	***IP2***	***IP8***
Nominal				
Static (Table 1)	36.1	0.0	6.1	6.1
Dynamic (Table 2)	0	6.3	0.7	2.1
Total	36.1	6.3	6.8	8.2
Ultimate				
Static (Table 1)	36.1	0.0	6.1	6.1
Dynamic (Table 2)	0	18.8	0.7	2.1
Total	36.1	18.8	6.8	8.2

3.2 COOLING SCHEME

At IR2 and IR8, the D1 [2], the DFBX Feed Box [5] and the Inner Triplet quadrupoles [6] are combined together to form a cryogenic module and are connected to the LHC distribution system [7]. The magnet leads of D1 are arranged to face the DFBX. The heat shield line and the cooldown line of D1 are connected in series with the DFBX and the Triplet. The 1.9 K cooling and the beam screen cooling for the D1 are connected in parallel with the Triplet.

The flow schematics for D1 in the left and right sides of IR2 and IR8 are given in Figures 3, 4, 5 and 6. The dashed box indicates the responsibility of BNL. In Figures 3-6, X is the 1.9 K helium II heat exchanger tube. Y is the 1.9 K liquid fill line. CL is the cooldown line and C' is the beam screen supply. In the right side of IR, LD serves as quench relief and cooldown return. XB is the 1.9 K vapor return. E1 and E2 are heat shield cooling. CFV, JT and TCV are control valves for cooldown, steady state and flow respectively. SRV is a pressure relief valve. The corresponding nomenclature of these lines, to that given in the flow diagrams of DFBX Functional Specification [5], is also shown for easy reference. A detailed description of the piping connection and operation are given below.

3.3 1.9 K COOLING

In either side of the IR, the 1.9 K liquid is fed from a common 4.5–1.9 K heat exchanger shared with the Triplet. The D1 and the Triplet are cooled in parallel. The 1.9 K liquid is fed to higher elevation end of the D1 through JT2 and the CY line, [identified as CY2 in ref. 5]. The 1.9 K vapor is returned from the lower elevation end of the D1 through the XB line, to the 1.9 K vapor return line from the Triplet. The two return flows combine and enter the low pressure side of the 4.5–1.9 K heat exchanger.

Each D1 is configured with XB and CY lines that run from the lead end (near the DFBX) to the non-lead end. At each location one of the two lines is used, the other is not. The choice is dependent upon which end of the magnet is at the higher elevation as described above. The unused line is labelled "unused" in Figures 3 – 6.

3.4 HEAT SHIELD COOLING

The heat shield cooling of D1 is in series with the Triplet and the DFBX. Both the E1 and E2 lines in the D1 cryostat are used.

In the left side of the IR, E2 is connected to the shield line of the DFBX (identified as Ex in ref. 5) as shown in Figures 3 and 5. The flow exits from E1 in the D1 cryostat through a line identified as E2 in ref. 5 to the F Header. Valve TCV1 is used to control the temperature of the shield below 75 K. TCV1 shall be sized for the total shield heat load of the D1-Triplet-DFBX cryogenic module.

In the right side of the IR, E1 is connected to the shield line of the DFBX as shown in Figures 4 and 6. The flow exits from E2 in the D1 cryostat through line (identified as E2 in ref. 5) to the F Header. Valve TCV1 is used to control the temperature of the shield below 75 K. TCV1 shall be sized for the total shield heat load of the D1-Triplet-DFBX cryogenic module.

3.5 300 - 4.5 K COOLDOWN OPERATION

The 300 – 4.5 K cooldown operation of D1 is in series with the Triplet. The flow direction of the cooling helium is from the low elevation end to the high elevation end. In the left side, D1 is upstream of the Triplet. In the right side, the Triplet is upstream of D1.

In the left side of the IR as shown in Figures 3 and 5, the cooldown line CL is connected to the C Header (through the line identified as LD1 in ref. 5). When CFV opens, helium flows from the C Header through CL to cool D1 and the Triplet. Helium returns to the D Header from the Triplet.

In the right side of the IR as shown in Figures 4 and 6, the cooldown line is connected to the Triplet through the DFBX. After cooling the Triplet, helium flows to cool D1. Helium returns through the LD line (line identified as LD4 in ref. 5) to the D Header, by opening relief valve SRV3.

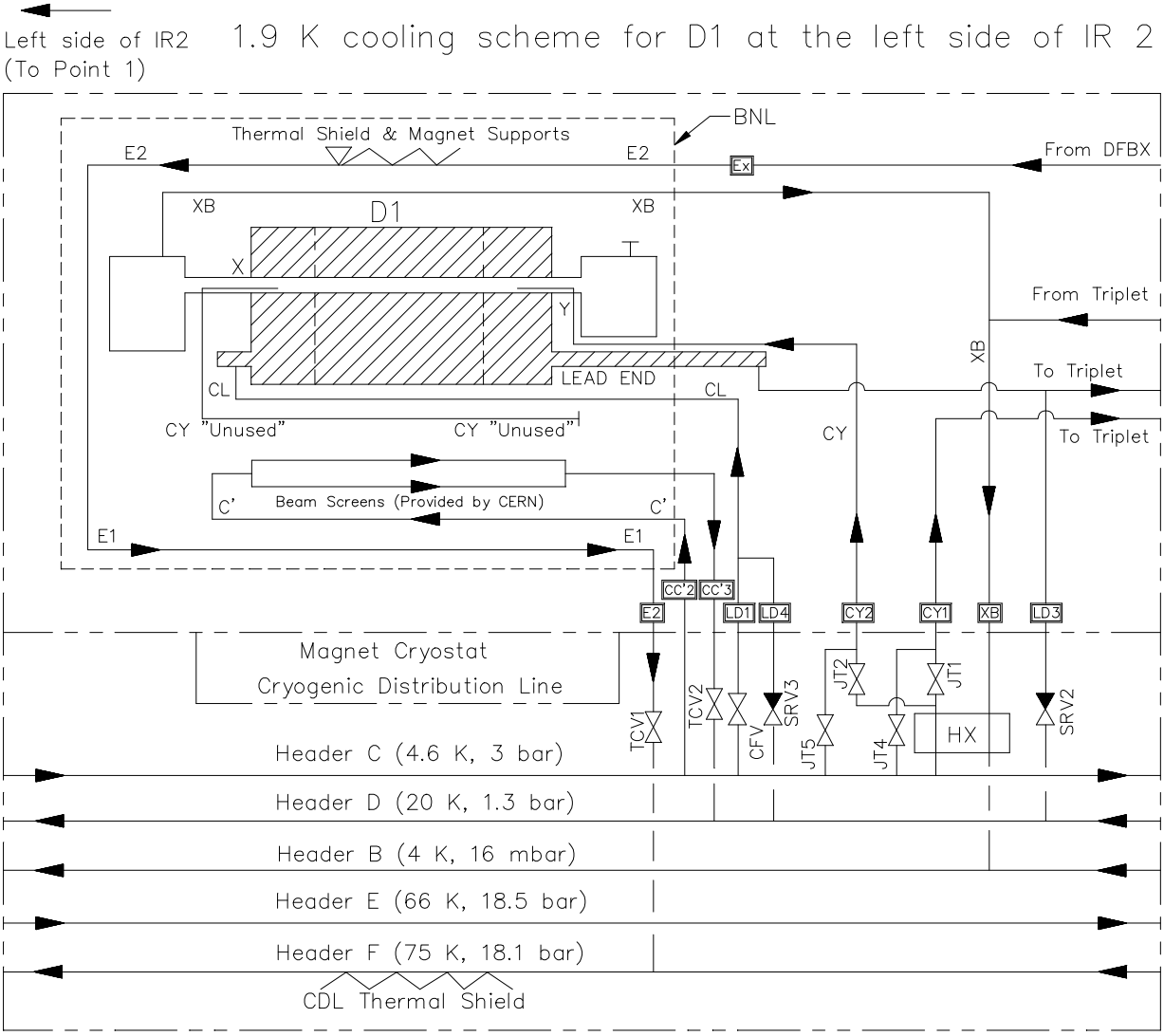
3.6 BEAM SCREEN COOLING

The temperature of the beam screen is kept below 20 K during machine operation. The helium supply line to the beam screen is connected to the C Header (through the line identified as CC'2 in ref. 5) as shown in Figures 3, 4, 5 and 6. Helium flows through the C' line to the far end of D1 where it enters the beam screen. After providing cooling to the beam screen, helium returns (through the line identified as CC'3 in ref. 5) to Header D. TCV2 will be sized based on the heat load of D1.

3.7 SAFETY RELIEF VALVE

In the D1-Triplet-DFBX module, there are three relief valves connected to the 1.9 K cold mass. In the left side, D1 is connected directly to safety reliefs SRV3 (through the line identified as LD4 in ref. 5) and SRV2 as shown in Figs. 3 and 5. In the right side, D1 is connected directly to SRV3 (through line identified as LD4 in ref. 5) as shown in Fig. 4 and 6. The safety relief valve SRV3 will release helium to the D Header if the pressure in the D1 cold mass becomes excessive. SRV2, connected to the piping between D1 and the Triplet, can provide additional venting should the pressure in D1 or the Triplet become excessive.

The D1 cold mass and the piping system in the D1 cryostat have a design pressure of 20 bar. The magnetic stored energy for D1 equals 350 kJ at 5000 A and 504 kJ at 6000 A operating current. Both the magnetic stored energy and the surface area of the D1 cryostat are less than that of an LHC arc dipole. Standard CERN relief valve used in the arc could be used. Alternatively, CERN could use above values to design a relief valve specific for the D1-Triplet. The relief pressure shall be set at 20 bar or less.



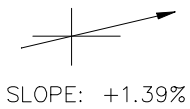


Figure 3. 1.9 K cooling scheme for D1 at the left side of IR 2. The pipe designations in boxes ( ) are those used in the DFBX Functional Specification [5].

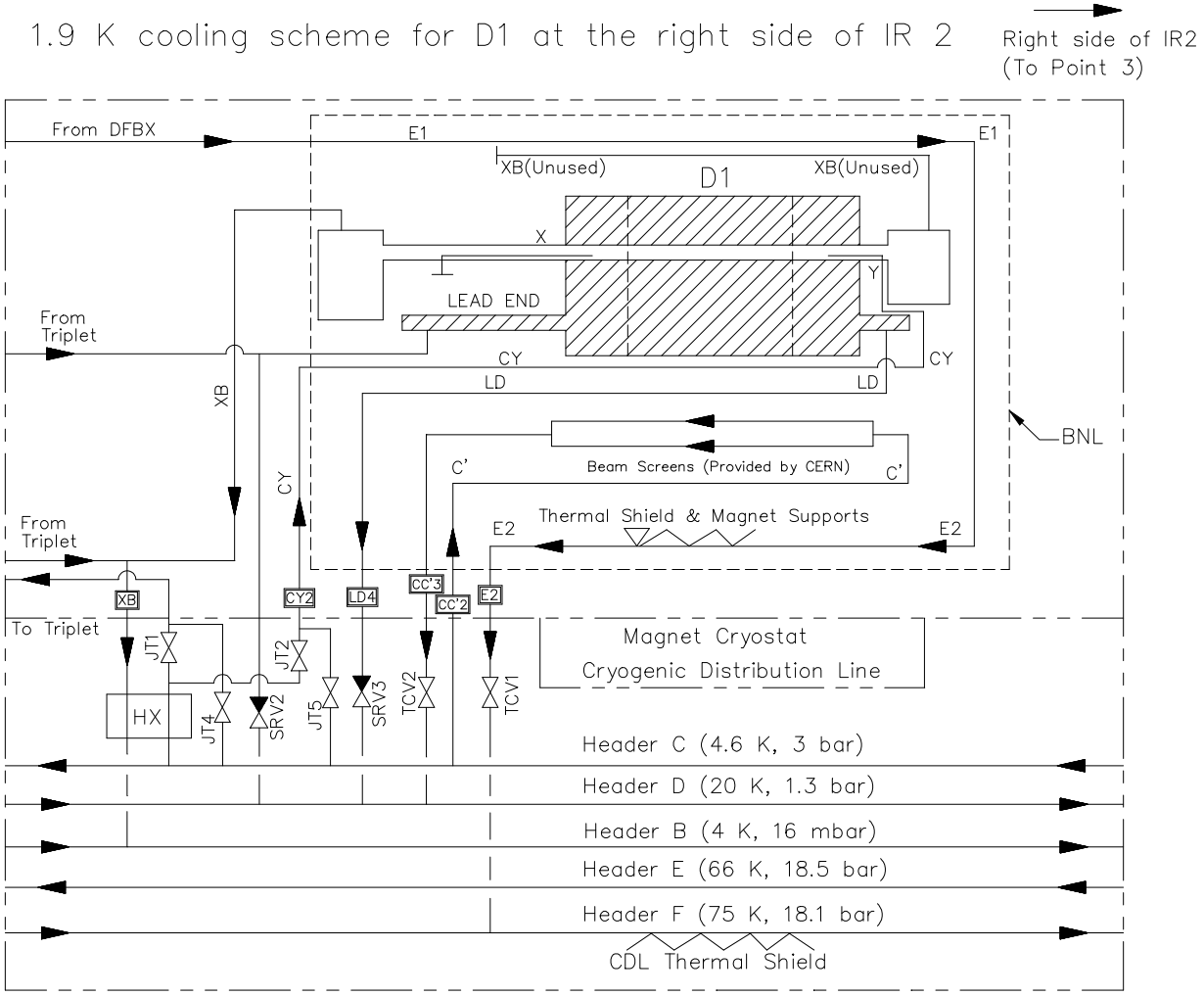
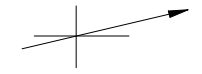


Figure 4. 1.9 K cooling scheme for D1 at the right side of IR 2. The pipe designations in boxes ( ) are those used in the DFBX Functional Specification [5].



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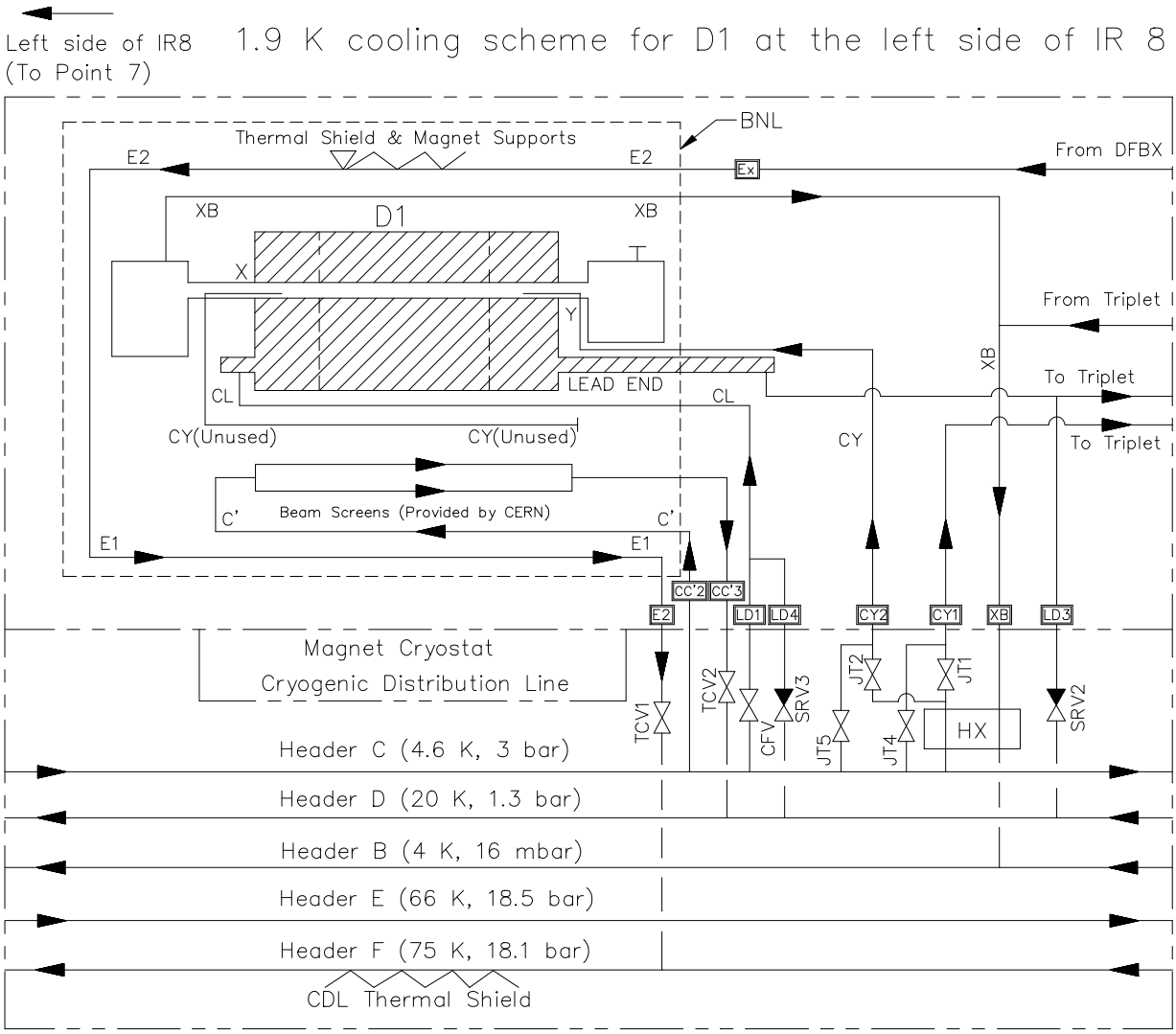


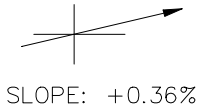


Figure 5. 1.9 K cooling scheme for D1 at the left side of IR 8. The pipe designations in boxes ( ) are those used in the DFBX Functional Specification [5].

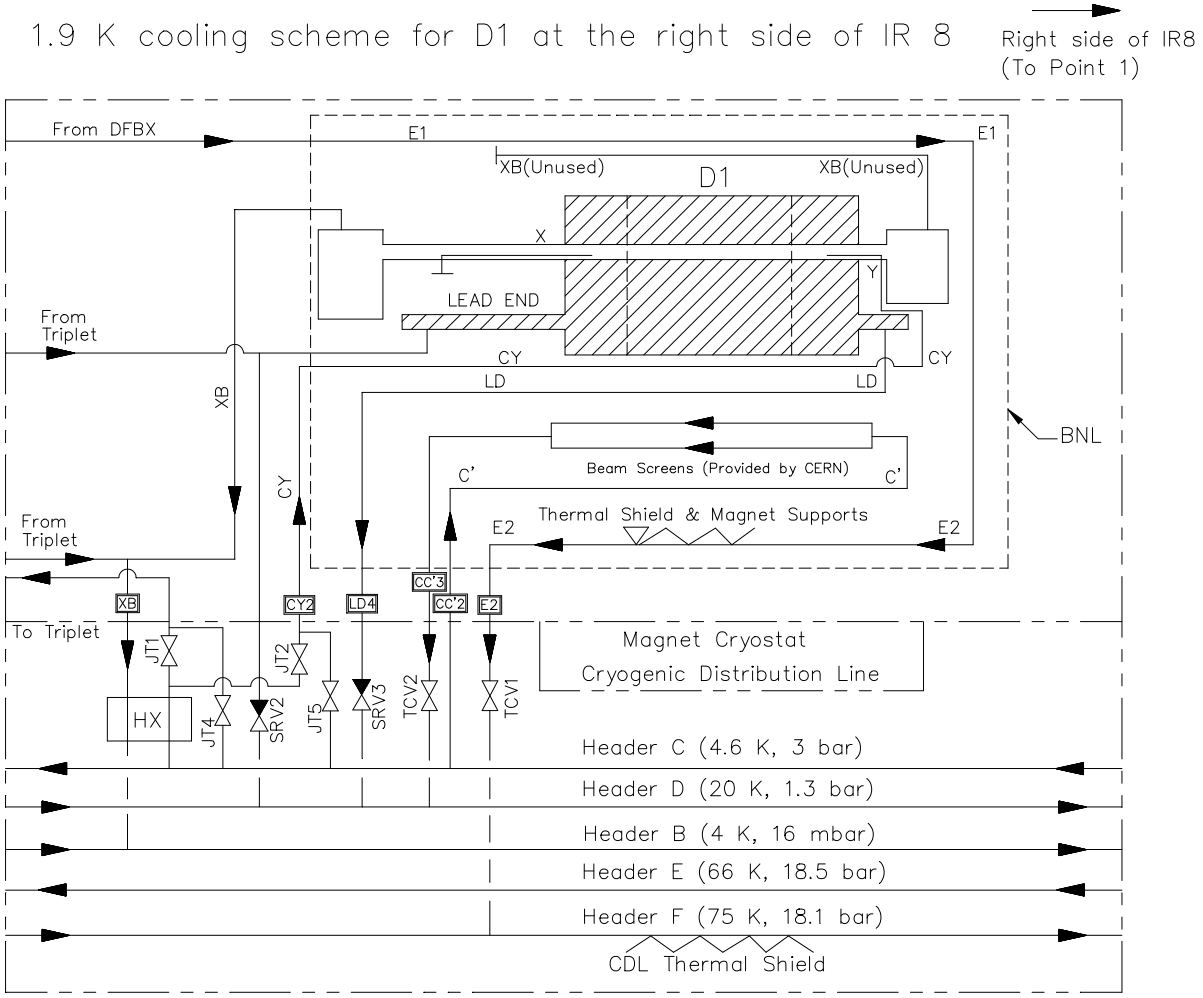
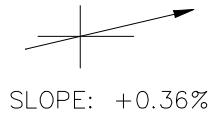


Figure 6. 1.9 K cooling scheme for D1 at the right side of IR 8. The pipe designations in boxes ( ) are those used in the DFBX Functional Specification [5].



3.8 CONTROL VALVES

The control valves shown in Figures 3-6 are provided by CERN and most need to be sized for the combined operating and cool-down conditions of the D1-Triplet-DFBX cryogenic system.

The D1 heat shield is cooled in series with the Triplet and DFBX and the temperature control valve TCV1 is sized for the total heat load of the D1-Triplet-DFBX cryogenic module.

The D1 beam screen is provided by CERN and is cooled independently of the Triplet. The temperature control valve TCV2 for the beam screen is based on the detailed design of the beam screen and the dynamic heat load of D1 (Table 3).

The 1.9 K cooling flow of D1 is in parallel to that of the Triplet. A suitable design condition for valves JT2 is 1 g/s flow with 3 bar and about 2 K at inlet, and 0.016 bar and 1.8 K at discharge. The percentage of liquid at discharge is about 88 %. The operating and design conditions are given in Table 4. This valve will also be provided by CERN.

Table 4. Operating conditions of the valve JT2.

Item	***Value***
Inlet	
Pressure (bar)	3
Temperature (K)	2
Outlet	
Pressure (bar)	0.016
Temperature (K)	1.8
Liquid Fraction (%)	88
Mass Flow (g/s)	
Operating Condition	0.4
Design Value	1.0

4. REFERENCES

1. "LAYOUT OF LONG STRAIGHT SECTION VERSION 6.2," LHC Drawings LHCLSX__0001 and LHCLSX__0002 (IR1); LHCLSX__0003 and LHCLSX__0004 (IR2); LHCLSX__0009 and LHCLSX__0010 (IR5); LHCLSX__0015 and LHCLSX__0016 (IR8).
2. "Superconducting Beam Separation Dipoles," LHC Functional Specification, LHC-MBR-ES-0001 rev 2.0, EDMS No. 110392.
3. "LBX Dipoles – D1," LHC Interface Specification, LHC-MBX-ES-0002, EDMS No. 248583.
4. Rob van Weelderen, Web publication, http://home.cern.ch/vanweeld/heatload/hlmagnets.html, version 3.0, 18 October 2000.
5. "Inner Triplet Feedboxes, DFBX," LHC Functional Specification, LHC-DFBX-ES-0100.00, EDMS No. 108074.
6. "Inner Triplet Systems at IR1, 2, 5 and 8," LHC Functional Specification, LHC-LQX-ES-0001, EDMS No. 108981.
7. "Distribution Feedbox Schematic," LHC Drawing LHCDFBX_0001, LBNL Drawing 24C3706.