Author
Jon Zbasnik

Department
Mechanical Engineering

Date
1 Nov 2002

MHG

Program - Project - Job: LHC IR Feedboxes
Cryogenics

Title: Lambda Plug R&D Report

1. Introduction

The DFBX requires two types of bus bar plugs that separate the 4.5K liquid helium vessel of the DFBX from the pressurized superfluid helium volume of the superconducting inner triplet quadrupoles and separation dipoles. *The plugs are called lambda plugs, after the term "lambda transition" that is used to represent the superfluid to normal transition because the specific heat variation with temperature around the transition temperature has the shape of the greek letter "lambda".*

One type connects to Q3, the outermost quadrupole magnet of the LQX assembly. This bus consists of 4 high-current conductors and 24 lower current conductors. The high current conductors each carry up to 7500 A and the lower current conductors each carry up to 600 A. Eight of these are required, one for each DFBX. This type is designated as the Q3 Lambda Plug

The other type connects to the superconducting D1 that is deployed at points 2 and 8 of the LHC. This bus requires 2 high current conductors to power the "A" and "B" leads of the superconducting D1. The conductors must carry up to 6000 A. Four of these are required, one for each of the DFBX at points 2 and 8. This type is designated as the D1 Lambda Plug.

This report presents the requirements, design features, fabrication outline, and test results of the LBNL R&D lambda plug for the DFBX.

2. Requirements

2.1 Electrical Requirements

2.1.1 Current Rating for Q3 Type

4 busses each with a 7500 A capability to power main inner triplet quadrupoles

24 busses each with a 600 A capability to power inner triplet corrector magnets

2.1.2 Current Rating for D1 Type

2 busses each with 7500 A capability to power D1 separation dipole

2.1.3 Voltage Rating for Q3 and D1 Types

For each 7500 A conductor, 1500 VDC in STP helium or 5000 VDC in STP air, with all other conductors at ground potential.

Leakage current to be less than 20×10^{-6} A after 1 minute at voltage.

For each 600 A conductor, 600 VDC in STP helium or 2500 VDC in STP air, with all other conductors at ground potential.

Leakage current to be less than 20 x 10^{-6} A after 1 minute at voltage.

2.2 Mechanical Requirements

2.2.1 Magnet-Side Pressure Rating for Q3 and D1 types
20 bar abs. (275 psig) Design Pressure
30 bar abs. (420 psig) Test Pressure for R&D Plugs
25 bar gauge (365 psig) Test Pressure for Production Plugs

2.2.1 DFBX-side Pressure Rating for Q3 and D1 type
3.5 bar abs. (51 psig) Design Pressure
5.5 bar gauge (80 psig) Test Pressure for R&D Plugs
4.5 bar gauge (65 psig) Test Pressure for Production Plugs

2.2.3 Leakage Rate for Q3 and D1 types
Less than 0.1 atm – cc/s (helium) at Room Temperature (10 Pa-l/s)

2.3 Operational Requirements (These are to be satisfied in R&D program)

2.3.1 Thermal Cycles for Q3 and D1 Types
Satisfy leak rate in 2.2.3 after 50 thermal cycles (300 K⇒80K⇒300K)

2.3.2 Magnet Quenches for Q3 and D1 Types
Satisfy leak rate in 2.2.2 after 25 pressure pulses of Design Pressure in 2.2.1

2.4 Other Constraints
Production Process must be stable and repeatable
Must allow for reliable attachment to the DFBX helium vessel
Bus bars must be stable against quenching:
use the 7500 A bus developed by FNAL for the inner triplet quadrupoles
use the 600 A LHC rectangular corrector bus wire

3. Determination of Acceptable Leak Rate

We performed an experimental determination of the leak rate of air through a small diameter tube. The tube had a 0.006 inch (0.15 mm) diameter and was 2 inch (50 mm long). It is actually a 30 gauge stainless steel dispensing needle purchased from McMaster-Carr Supply Company that provided a convenient leak calibration standard.

Using a critical heat flux of 5.5 W/cm^2, the superfluid heat load for a 0.15 mm diameter path is approximately 1 mW. Compared with the heat load from conduction through the materials in the lambda plug, about 4 W for the worst case, this represents a negligible contribution.

Another consideration, from Tom Peterson, is that we want to limit the mass flow from the magnets into the DFBX helium chamber. The worst-case mass flow through a 0.15

mm diameter path through the lambda plug will be about 0.035 g/s for a 1.7 bar pressure differential. This rate is less than the specified leakage rate across the CERN superfluid safety relief valves of .01 g/sec for a 0.1 bar pressure differential and therefore is acceptable for LHC operation.

A final consideration is that the small diameter path will limit mass flow during high pressure tests at LBNL, the DFBX Vendor site, and at CERN to levels that will minimize the impact on carrying out the tests.

The leak rate through the needle was determined using a classical rate of rise measurement in which a closed volume was evacuated and then allowed to be pressurized by atmospheric pressure through the needle. Figure 3 –1 shows the test setup used

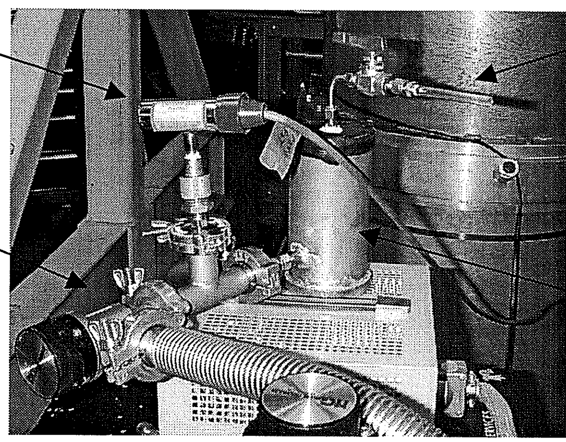


Figure 3-1. Rate of Rise Test Setup.

The pressure reading as a function of time is shown in Figure 3-2.

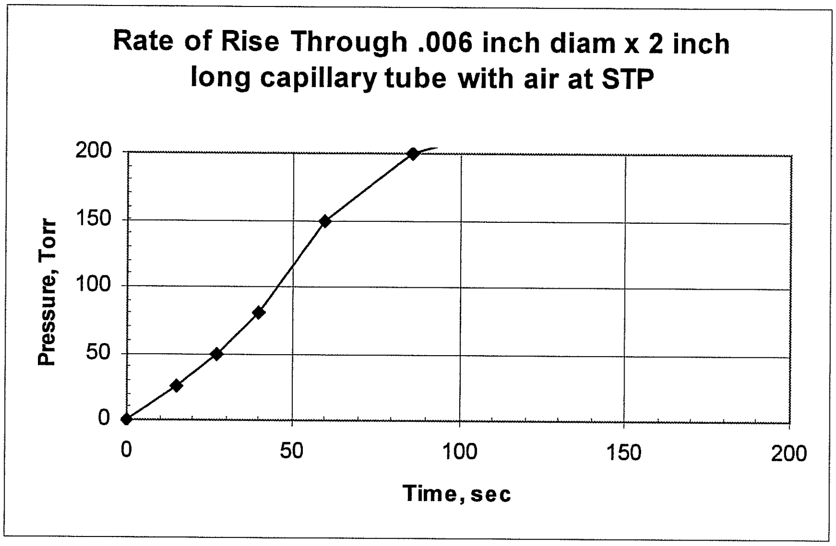


Figure 3-2. Rate of Rise Results.

The volume of the trapped volume is 310 cm^3 (0.31 liter) and we see that the pressure rose 200 Torr in 86 sec. The leak rate is therefore,

Leak rate = 200 Torr x .31 liter/86 s = 0.72 Torr-l/s (air)
= 0.72 x 1.33 = 0.96 atm cc/s (air)
= 0.96 x 2.7 = 2.6 atm cc/s (helium)

Therefore, our requirement that the leak rate of the lambda plug shall be less than 0.1 atm cc/s (helium), as stated in 2.2.3 above, gives a very large safety margin in performance since the leak rate could be as high as 2.6 atm cc/sec (helium) and still be acceptable for LHC operation.

4. Lambda Plug Design and Fabrication

The basic concept of the design is to pot the conductors in an insulating block of NEMA G10-CR, and then pot this in a stainless steel housing.

Figure 4-1 shows an R&D version (PG-4) of the plug. The outer diameter of the stainless steel housing is 6 inch (152 mm) and it tapers as a conventional weldneck pipe flange to the 3.5 inch (88.9 mm) outer diameter pipe on the right hand side. In Figure 4-1 the conductors are about 8 inch (200 mm) long whereas in the production versions they will be about 96 inch (2.44 m) long.

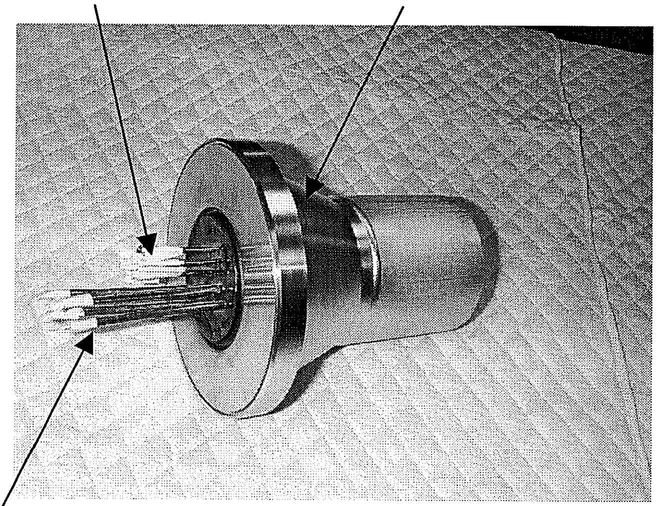


Figure 4-1. R&D lambda Plug Assembly

Figure 4-2 shows R&D Plug PG-4 with its closeout welding completed. The left side simulates how the lambda plug assembly will attached to the bus duct at LBNL, and the right side simulates the field welding that will performed by the Vendor to seal weld the bus duct assembly to the DFBX liquid helium vessel. The clamping ring provides mechanical support for the seal weld. A sketch of the cross section is shown in Figure 4-2.1.

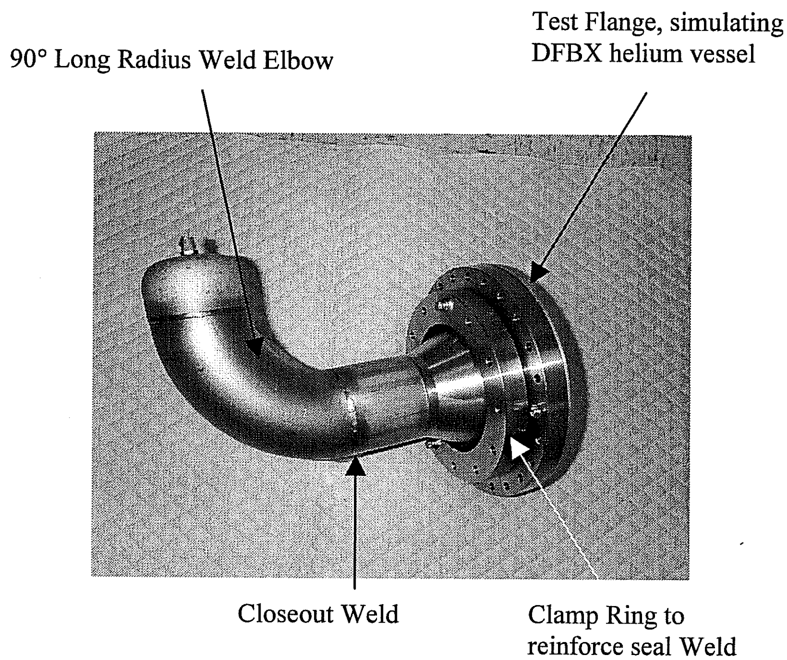


Figure 4-2. R&D Lambda Plug with closeout welding completed.

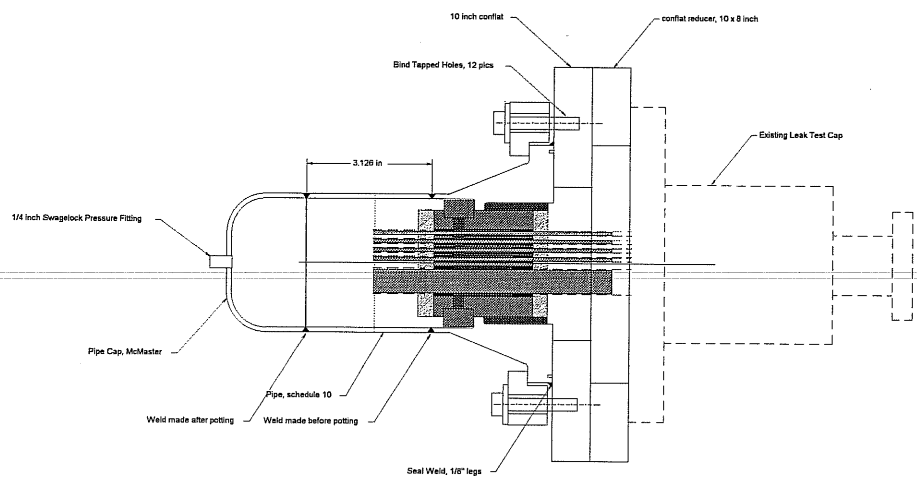


Figure 4.2-1 Cross-section of Lambda Plug

The heart of the lambda plug assembly is a two-piece NEMA G-10CR insulator block shown in Figure 4-3. The design allows for proper spacing and orientation of the conductors. The plane of reinforcement is parallel to the faces of the plug. After the two parts are assembled, the configuration allows for the conductors to be encapsulated in Stycast 2850MT (blue) epoxy, using hardener 24LV.

Figure 4-4 shows some of the steps in filling the Rutherford cables with 60/40 Sn/Pb solder. Solder foils are inserted into the cable, following a suggestion from V. Benda of CERN, to ensure that the interior of the cable is completely filled with solder. The cable with the inserted foils, along with additional solder foils, are laid into the heater box where the parts are heated with cartridge heaters. Heat sinks are used to prevent the solder from wicking beyond the area that will be potted in the insulator block.

Figure 4-5 shows the insulated busses, and the gap in their insulation that will be located inside the insulator block can be seen.

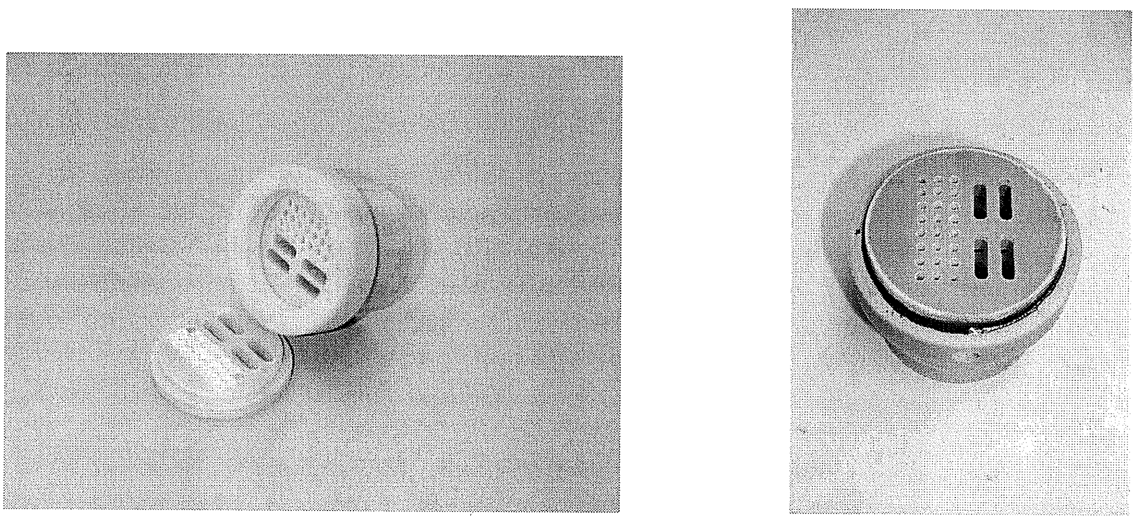
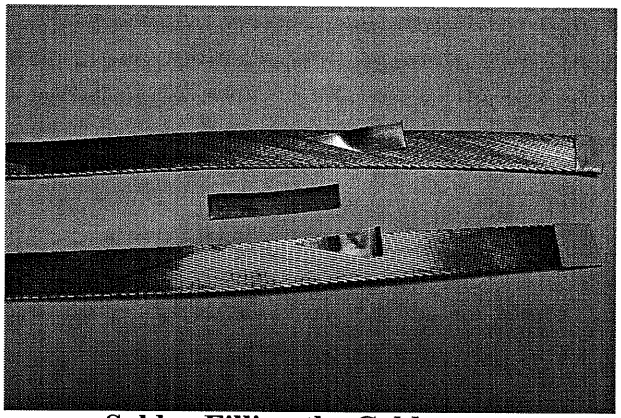
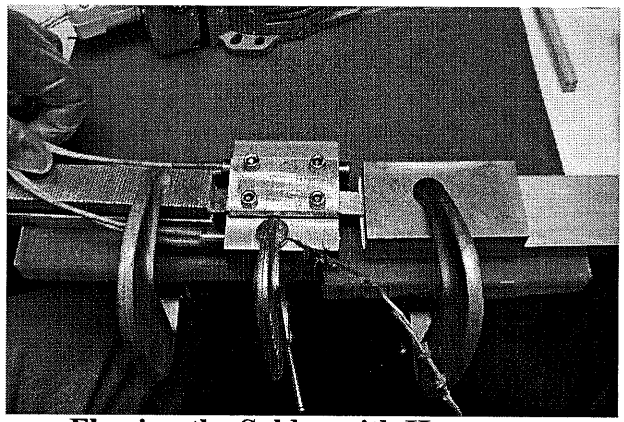


Figure 4-3. DFBX Lambda Plug Insulator Block

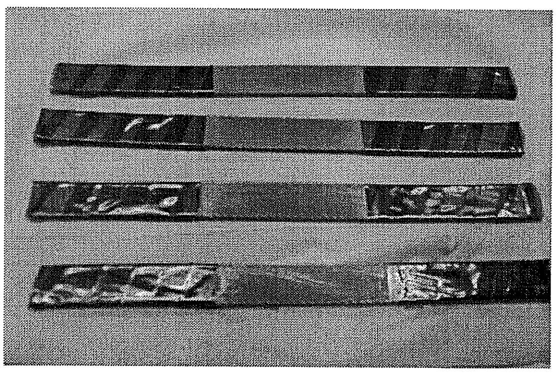


Solder-Filling the Cable

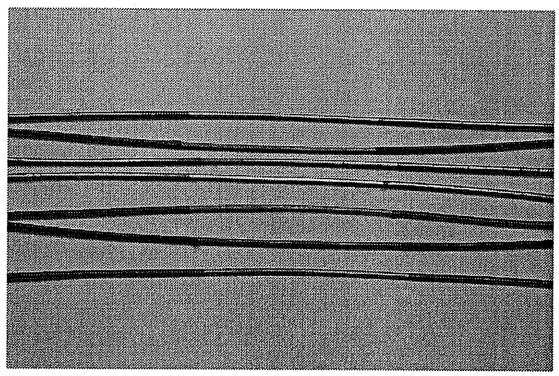


Flowing the Solder with Heaters

Figure 4-4. Cable Filling Steps



7500 A Main Magnet Busses

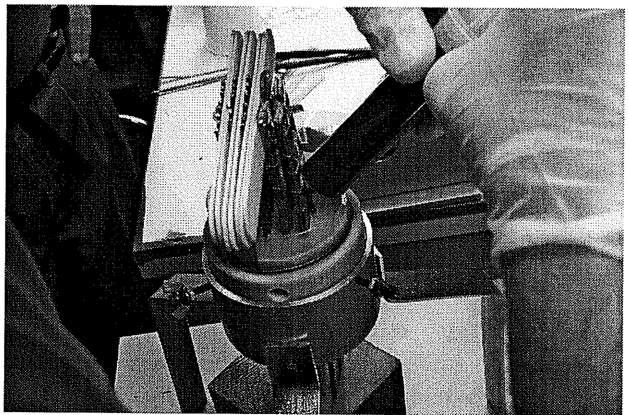


600 A Corrector Busses

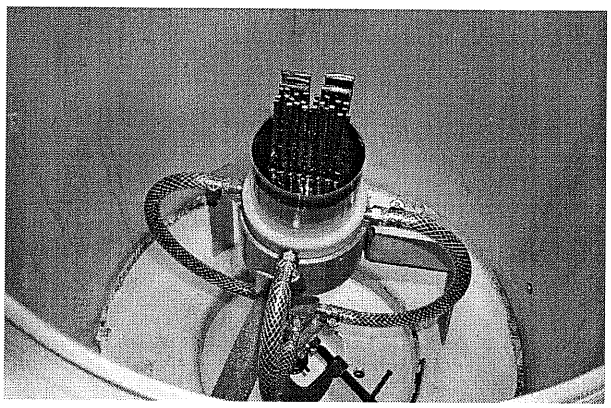
Figure 4-5. Insulated Busses

The insulated conductors are potted in the insulator block with Stycast 2850MT (blue) with 24LV hardener by a two-step process shown in Figure 4-6. The procedure is quite detailed and careful attention must be given to surface preparation, handling, and environmental control.

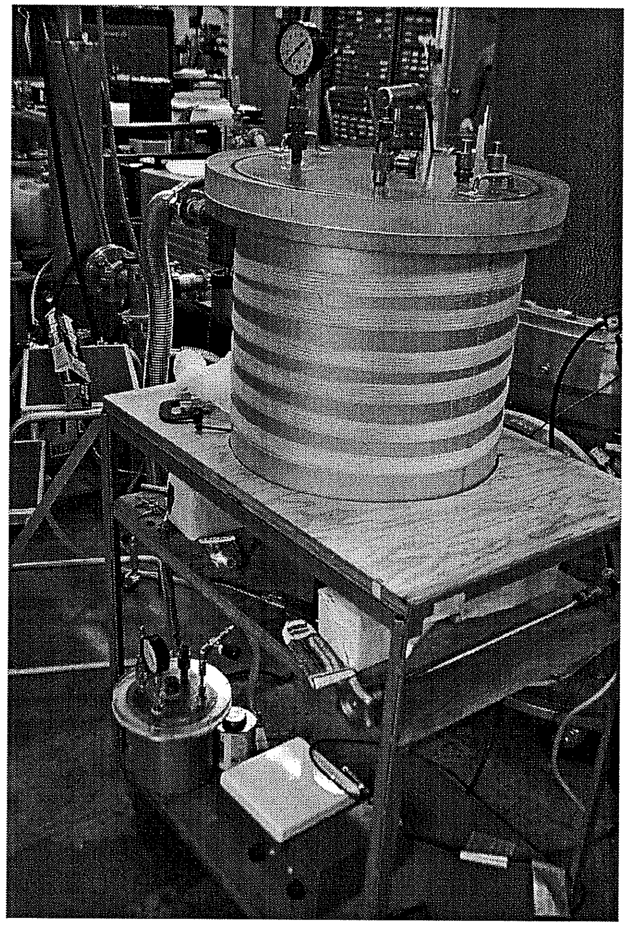
After 3 thermal cycles and a leak check to verify leak-tightness the insulator block is potted in the stainless housing using Stycast 2850MT (blue) with hardener 24LV.



Step 1 – Potting the "magnet" end



Step 2 – Fill the Insulator Block by Injection in Vacuum Chamber



Potting Chamber

Figure 4-6. Potting the Conductors in the Insulator Block

The final step in the fabrication of the R&D Lambda Plugs is the closeout and seal welding. The welding simulates the anticipated thermal stresses that would be encountered in the actual fabrication and installation.

The weld to the 3.5 inch section is done by:

- installing a backing ring on the piping that will be welded to the lambda plug,
- tack welding the pieces into the proper position,
- making a GTAW fusion root pass with 1-inch (25 mm) long welds, skipping around the circumference to control distortion, pausing between skips to allow the part to be cooled to room temperature between skips with a "Cool Gun",
- making a GTAW seal pass with ER316L filler wire, skipping, pausing, and cooling as was done in the fusion root pass
- the temperature at the area of the epoxy potting is maintained below 30C

The weld to the test flange, simulating the welding required to attach the lambda Plug Assembly to the DFBX liquid helium vessel, is also done in a discontinuous manner using 1 inch (25 mm) long welds, pausing between welds and allowing the part to be cooled to room temperature with a "Cool Gun" between welds. Originally, we assumed the weld to be a fillet weld with 0.125 inch (3.2 mm) legs, but we found that we could reduce the fillet leg to 0.06 inch. Welding is done using the GTAW process; the 0.125 fillet required ER316L filler wire to be used, but the 0.06 fillet can be made with a fusion process. The temperature of the epoxy regions is maintained below 30C during this welding.

5. DFBX Lambda Plug R&D Testing Results

The final series of R&D lambda plugs is designated as PG-6, and consist of 5 samples,

PG-6a: Insulated main conductors, insulated corrector conductors, 0.125 fillet weld
PG-6b: Mixed too much epoxy; this hardened prematurely due to exotherm heating, prevented proper potting
PG-6c: Insulated main conductors, bare corrector conductors, 0.125 fillet weld
PG-6d: Insulated main conductors, bare corrector conductors, 0.06 fillet weld
PG-6e: No conductors (solid G-10 plug), 0.06 fillet weld.

A summary of the test results is given in Tables 5-1.

Table 5-1. Summary of R&D Tests on PG-6 series Lambda Plugs

Test Sequence	PG-6a	PG-6b	PG-6c	PG-6d	PG-6e
In-Process Testing♣♦	All okay	Incomplete step 2 potting [a]	All okay	All okay	All okay
Leak rate after potting in housing		Plug was not used		$<1 \times 10^{-10}$ atm cc/s	
Leak Rate after 2 thermal cycles			$<1 \times 10^{-10}$ atm cc/s	$<1 \times 10^{-10}$ atm cc/s	
Leak Rate after welding	.035 atm cc/s [b]		.069 atm cc/s [c]	7×10^{-10} atm cc/s	3×10^{-10} atm cc/s
50 thermal cycles[d]	done		done	done	done
Post-thermal cycling leakage	.035 atm cc/s		0.10 atm cc/s	3.6×10^{-3} atm cc/s	7×10^{-8} atm cc/s
R.T. Pressure Test to 420 psig (29 bar)	Passed, not deformed		Passed, not deformed	Passed, not deformed	Passed, not deformed
Post-pressure test leakage	.035 atm cc/s		0.1 atm cc/s	7.5×10^{-3} atm cc/s	2.5×10^{-8} atm cc/s
Cold Pressure Test to 420 psig	Passed, not deformed		Passed, not deformed	Passed, not deformed	Passed, not deformed
25 quench pressure pulses	Not done		Passed	Passed	Passed
Post-pressure test leakage	.025 atm cc/s		.069 atm cc/s	6.1×10^{-3} atm cc/s	1.2×10^{-8} atm cc/s
R.T. Pressure test DFBX side to 80 psig	Not done		Passed	Passed	Passed
Cold Pressure test DFBX side to 80 psig	Not done		Passed	Passed	Passed
7500 A HiPot to 5 kV	Ok to 5 kV in air		One tripped at 4.9 kV in air	Ok to 5 kV in air	Not applicable
600 A HiPot to 2.5 kV	Ok to 2.5 kV in air		Not insulated	Not insulated	Not applicable

Notes:
a. An excessive amount (1000 g) of epoxy was mixed and the exothermic heat generated caused the epoxy to harden before the plug was filled.
b. No change in leak rate due to welding.
c. We have evidence that the leak rate increased upon welding. We will check this carefully in PG-6d.
d.Thermal cycling is done by plunging the assembly into a bath of LN_2 , held for 1 hr, then pulled out and warmed in air for 1 hour, etc.

6. Conclusions

- The R&D results on the PG-6 series plugs demonstrate that we have developed a lambda plug that meets the requirements stated in section 2.
- The room temperature leak rate requirement of 0.1 atm cc/sec (helium) provides an operational safety factor of about 10 when compared to the leak requirement for the CERN pressure safety relief valves on the pressurized superfluid system.
- We have made three plugs in a row with conductors that satisfy the leak rate requirement after thermal cycling and pressure testing at room temperature and liquid nitrogen temperature.
- The testing included simulation of the welding needed to carryout the closeout of the bus duct piping and also the welding needed to attach the lambda plug assembly to the DFBX liquid helium vessel.
- A fourth plug was made without conductors to provide additional confidence that the seal weld to the DFBX liquid helium vessel will not cause excessive degradation of the bond between the stainless steel housing and the G-10 insulator block.

7. Acknowledgements

The efforts of Steve Ferreira, Paul Bish, Roy Hannaford, Nate Liggins, Jim Swanson, Jim O'Neil, Bill Gath, Dave Anderson, Ahmet Pekedis and Phil Bach in carrying out the work reported in this report is gratefully acknowledged. Steve, Paul, Roy, Nate, Jim S., and Jim O. diligently developed the techniques and applied them to make the successful R&D lambda plugs. Bill, Dave, and Phil developed the techniques and carried out the pressure, leak, and electrical testing.