Design Considerations for Beam Tube Penetration of a Liquid Argon Collider Detector

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Abstract

At the D-Zero collider detector, the Tevatron beam must pass through the massive End Iron and liquid argon End Calorimeter in order for proton/anti-proton collisions to occur within the Central Tracking chamber. We discuss the brazed beryllium (low atomic mass) beam tube through Central Tracking and the necessary magnetic shielding of the beam tube through the End Calorimeter cryostat and End Iron. Vacuum system issues, including custom ion pumps, low profile all-metal valves, reduction of outgassing within the beam tube, and anticipated pressure distribution are presented. The requirement of access to the Central Tracking by rolling back the liquid argon filled End Calorimeter cryostat is addressed with flexible bellows, integral heaters, and force sensors to protect the beam tube. Installation, collider roll-in, and interface to low-beta quadrupole magnet details are also presented. Implications for SSC configuration within collider facilities are evident.

I. Introduction

The D-Zero collider detector (named after its location on the ring) is presently being constructed adjacent to the Tevatron accelerator at Fermilab. When complete, the 4534 tonne [5000 ton] detector will be rolled into Collision Hall where connections to the Tevatron are installed. In addition, Fermilab's Main Ring (injector to the Tevatron, but sharing the same tunnel), which is 206.4 cm [81.25 in] above the Tevatron at D-Zero, will pass through the collider detector.

The D-Zero detector consists of a 152 cm [60 in] diameter, room temperature Central Tracking detector surrounded by three 518 cm [204 in] diameter liquid argon calorimeters. The three cryostats are enclosed by Muon detectors and a massive toroidal iron. A primary goal of the D-Zero detector is hermetic calorimetry; that is, the measurement of all the energy associated with p-pbar collisions (protons and anitprotons). Accordingly, only a minimum of real estate is allowed for accelerator, vacuum system, and associated hardware. An additional design constraint is the requirement that the End Iron and End Calorimeter cryostats be allowed to roll back for access to the Central Tracking.

II. Tevatron

The configuration of the Tevatron through D-Zero can be divided into four components: the beryllium section through Central Tracking, the pass through the End Calorimeter cryostats, the section within the End Irons, and the spool pieces, or removable connection to the final focusing magnets.

A. Central Tracking

The section through the Central Tracking; that is, the beam tube which surrounds the actual collision point, is fabricated of rolled beryllium. Beryllium is chosen for its low atomic mass; absorption of energy should occur in the detector, not in the beam tube. Rolled beryllium is preferred since extrusion results in reduced ductility. In the unlikely event of a failure in the beryllium beam tube, a simple rupture would be a small disaster, as compared to shattering of brittle beryllium, pieces of which would undoubtedly be drawn into a significant length of the accelerator by the vacuum. The beryllium tube is 5.08 cm OD x 147.3 cm long x 0.051 cm wall thickness [2.00 in OD x 58 in long x 0.020 in wall] with aluminum alloy braze along both the longitudinal seam and the end connections to stainless steel tubes.

A pair of formed bellows at each end allows for misalignment of the End Calorimeter cryostats, relative to the Central Tracking, with only a small moment introduced on the beam tube. In order to allow installation through the Central Tracking's Vertex Chamber (innermost detector) a bellows OD of 5.84 cm [2.3 in] was specified. Furthermore, a minimum ID of 4.83 cm [1.9 in] was required in order to obtain a guaranteed minimum clear aperture of 4.75 cm [1.87 in]. The assembly is positioned by miniature roller bearings mounted at the end plates of the Vertex Chamber.

B. End Calorimeter

A 5.08 cm [2 in] OD stainless steel tube, wrapped with tape for electrical isolation, passes inside the End Calorimeter cryostat's warm (vacuum vessel) tube, which has an ID of 5.78 cm [2.277 in]. Actually, the ID of the Inner Hadronic Module, the centerpiece of the End Calorimeter, is only 7.83 cm [3.084 in]. Within 1.27 cm [0.5 in] of radial space, we are required to fit the cold cryostat tube, vacuum space sufficient for 15 layers of superinsulation, a heater, and the warm (vacuum vessel) tube. Energizing the heater, thereby bringing the vacuum vessel tube as high as 100^{0}C, enables us to be certain that no frost has accumulated between the accelerator tube and the vacuum vessel tube. Although less than 0.63 cm [0.25 in] of radial vacuum space exists, we believe that frost is unlikely as we plan to provide a continuous purge of dry (instrument) air. We intend to operate the heaters only in preparation of, and during, an End Calorimeter cryostat roll. From a vacuum system standpoint, a cold accelerator tube during operation is actually an advantage.

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As an additional safeguard, load cells are to be installed around the bellows pair downstream (away from collision point) of the End Calorimeter. Holding the accelerator tube fixed in space during an End Calorimeter cryostat roll, the load cells will be used to determine the force imposed on the accelerator tube. Tests are currently in progress to determine the magnitude of the force which will be allowed. Specifically, we're studying the combined effect of vacuum load and axial compression on a thin wall stainless steel tube.

Bellows are necessary on the cold and warm tubes of the End Calorimeter cryostat due to the expansion and compression of the heads during pressurization and pump-down. Since the calorimeter, and cold cryostat, are expected to undergo a vertical displacement of -0.48 cm [-0.190 in] during cool-down to 87 K, while the warm head has zero displacement, the warm tube will be installed off-center with respect to the cold tube. Greater than expected motion can be accommodated by the upstream and downstream bellows of the cold tube. Since the effort required to replace any of these bellows is so significant, we are planning 2-ply bellows, where each ply is sufficient for the pressure and temperature. Presently, we are working with vendors to develop a configuration where each ply is terminated in a separate weld, with an integral test port to the between ply region. Lines would be installed to an outside port on the vacuum vessel where leak testing could be performed when desired.

C. End Iron

The pass through D-Zero's End Iron actually occurs through the SAMUS (Small Angle MUon Sensor, a toroid placed inside the End Iron), where a 50.8 cm x 50.8 cm [20 in x 20 in] opening has been allowed for the accelerator and the vacuum system components. Custom ion pumps have been sought where the beam passes through the center of the pump. The pump is custom in its overall shape only, as we attempted to allow the fabricator to use standard 20 liter/sec diode pump elements inside custom magnets and enclosure. We specified a minimum of 60 liter/sec, at 10^{-6} microns. In addition, we're installing a pair of dual filament nude ion gauges and a pair of convectron gauges.

All unused space is being filled with lead or, for the center 20.3 cm [8 in] square, tungsten shielding. The complete configuration of approximately, 3630 kg [8000 lb] is mounted on a stainless steel support with linear bearings inside the SAMUS toroid. This "cart," containing vacuum system components and shielding, will remain fixed in space while the End Iron is rolled. In essence, we have an inverted railroad: our "train" stands still while its rails are moved. The cart, vacuum system, and shielding will be assembled and leak checked in a shop area, then installed as a complete unit. The design of individual shield blocks allows disassembly for maintenance without removing the entire unit.

D. Connection to Low Beta Quadrupole Magnet

The 6.3 cm [2.5 in] OD spool piece connecting the SAMUS cart vacuum components to the final low beta quadrupole magnet is inserted between two identical gate valves after the collider detector is rolled into Collision Hall. The chosen valves were required to fit within the 50.8 cm x 50.8 cm [20 in x 20 in] opening in the SAMUS during the rolled-out configuration of the End Iron. Since the beam is centered inside the opening (actually, center ± 0.63 cm [1/4 in]), we are left with less than 25.4 cm [10 in] on either side of center to fit an entire gate valve! We are using a pendulum type gate valve with a 14.94 cm [5.88 in] aperture; however, the accelerator beam will pass through the aperture of the valve 3.49 cm [1.375 in] off-center. This eccentric installation allows the valve to fit inside the SAMUS opening.

The gate valves were ordered with pump-out ports on both sides. Hence, the vacuum system opposite the gate seal side of the valve can be pumped down through either of these ports. When installed the gate seal side will be towards the magnet on both valves. The pump-out port on the magnet valve will be used to pump-out the spool piece, the pump-out port on the SAMUS cart valve will be used to pump-out the accelerator tubes of the SAMUS toroids, End Calorimeter cryostats, and Central Tracking (including the beryllium section). A single convectron gage installed on the unused pump-out port of the magnet valve will be used to used to permit gate valve operation. The pump-out on the SAMUS cart valve will be tee-ed with a 1.2 atmd [17 psid] burst disk in order to protect the beryllium from over-pressurization. Lastly, a pair of permanent magnets, to correct for D-Zero's stray magnetic field, will be installed over the spool piece. The magnets are installed in halves, with fixturing required to control their mutual attraction during installation.

E. Predicted Vacuum

The configuration of the Tevatron; that is, varying inside diameters and outgassing rates, suggests using a numerical approach to estimate the pressure profile. ANSYS[R] was used to model the Tevatron vacuum system through D-Zero [1]. Treating the problem as though it were a thermal analysis, values for the conductance (thermal conductivity), outgassing rate (heat generation rate), ultimate pressure (fixed temperature), and pumping speed (convection coefficient) are entered. ANSYS then calculates the nodal pressures (temperatures). The results are piecewise parabolic, as expected. The outgassing rate for beryllium has been taken from rate of rise tests on similar tubes at Fermilab. The outgassing rate for electropolished stainless steel was estimated from the published literature. Although the results are clearly dependent upon the entered outgassing rates, the ANSYS thermal analogy proved a useful tool for the comparison of alternative system designs.

Although all components will be pre-baked, it is unavoidable that they be let up to atmosphere during installation. An in situ recovery bake is impossible due to the sensitive electronics of the Vertex Chamber. We plan to purge the system with dry nitrogen while open to atmosphere, thereby minimizing the recondensation of water vapor. This procedure was simulated with a beryllium assembly that had previously been baked at 200°C three times without venting: 4

R ANSYS is a registered trademark of Swanson Analysis Systems, Inc.

hours, 8 hours, then 8 hours. Afterwards, the tube was vented to dry nitrogen, and purged for 24 hours. Results indicate that ultimate pressure was approximately equivalent to that of the tube following the first, 4 hour, bake.

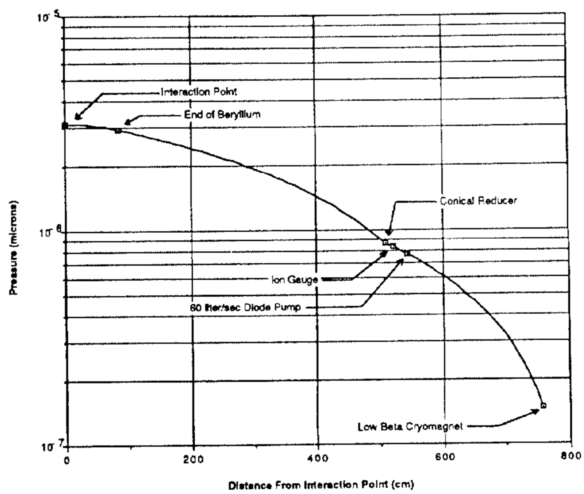

Figure 1. ANSYS results for Tevatron Pressure Profile through the D-Zero Collider Detector.

III. MAIN RING

A. General Layout

The Main Ring is an injector to, and shares the tunnel with, the Tevatron. As the accelerator approaches D-Zero Collision Hall, the Main Ring is ramped up so as to pass through the experiment in a less critical location. Specifically, there are penetrations in the End Irons and cryostats located 206.4 cm [81.25 in] above the Tevatron. At the D-Zero Collider Detector, a straight section 1829 cm [720 in] long occurs between a cluster of four triode pumps at each end. Particle scatter within the calorimeters, due to proton beam/gas particle interaction must be minimized. Accordingly, extra triode pumps are being added downstream (both directions) of the new section of beam tube described here. Whereas O-ring seals are generally used on the Main Ring, the span between ion pump clusters at D-Zero will use only all-metal components. All tubing is mechanically polished, then electropolished to minimize outgassing surface area. All-metal gate valves are installed at each end, near the ion pumps to isolate the Main Ring straight through the experiment. Similar to the Tevatron valves, these Main Ring gate valves have been ordered with pump-out ports installed on the valve body. The span between gate valves is to be pumped down through these pump-out ports.

Once installed, it is our intention to never let the system up to atmosphere. The section between gate valves will have heat trace installed, allowing for a recovery bake at 200°C, or defrosting before rollback of the End Calorimeters. This concern is similar to the Tevatron pass through the End Calorimeters; however, the clearances, including the insulating vacuum space between vessels, for the Main Ring are much more generous.

The entire length of Main Ring tube is wrapped with several layers of magnetic shielding to intercept D-Zero's stray field; hence, let the Main Ring beam pass through the experiment in a nearly field free beam tube. An optimized layup of high permeability nickel-iron, silicon-iron, and carbon steel tube was specified. Between the two gate valves, located just beyond the rolled back position of the End Irons, the Main Ring will be a straight 12.7 cm [5.0 in] OD tube. Due to the complicated alignment challenge presented by multiple penetrations of the Tevatron and Main Ring through two End Irons, three cryostats, three calorimeters, and Central Tracking, the Main Ring straight section will not necessarily be installed parallel to the ideal beam path. Clearly, any compromises of location of these massive devices will be at the expense of the Main Ring, not the Tevatron. Accordingly, pairs of formed bellows are used at each end to allow for misalignment. The beam tube assembly is supported at each end of the Central Calorimeter's cryostat, and at each end of both End Irons. The roll-out feature of the End Iron required that the supports be adjustable, to allow for the unknown initial position, and spring loaded, to allow for lateral motion during an End Iron roll.

B. Predicted Vacuum

Main Ring vacuum is generally 5 x 10^{-5} microns. For a beam tube of 12.7 cm [5 in] dia, electropolished and baked in situ, the pressure gradient is small; hence, the expected pressure is close to that of the triode pump's ultimate pressure. The actual pressure drop from the pump cluster to the center of the span can be calculated by [2]:

$$\Delta P = qBL/2C \qquad (1)$$

where: q = outgassing rate
B = inside perimeter of tube
L = length
C = conductance

For the Main Ring configuration, ΔP is estimated to be 0.6 x 10^{-11} microns Since it is clear that we are installing more than sufficient pumping speed, in a system were outgassing has been minimized, the pressure of the Main Ring through D-Zero becomes primarily dependent on the ultimate pump pressure. Accordingly, we plan to install pumps with bake out kits in order to obtain their lowest possible pressure. Pumps, and the entire Main Ring tube through D-Zero, are expected to operate in the 10^{-6} micron range.

IV. REFERENCES

[1] Primdahl, Keith, "Using an ANSYS Thermal Analogy to Calculate Vacuum System Performance," FERMILAB-PUB, to be published.

[2] Roth, Alexander, *Vacuum Technology*, New York: Elsevier Science Publishers, 1989, p 133.