Chapter 11

Beam Vacuum Chambers

The muon storage volume, which lies within the 1.45 T magnetic field, is evacuated in order to minimize multiple scattering of muons and positrons. This is accomplished by a set of aluminum vacuum chambers, which also provides mechanical support for:

- the beam manipulation systems: the electrostatic plates of the quadrupole system, the collimators, and plates of the magnetic kicker system.
- the positron detection systems: the trace-back straw trackers and auxiliary detectors such as the fiber harp.
- the magnetic field measurement systems: $\sim$ 400 fixed NMR probes surrounding the storage volume, a set of rails for the trolley NMR system, and the plunge probe system.

The chambers from BNL E821 will be reused for E989, and we will make changes as described in the section below. The chamber design is detailed in the BNL E821 design report[1], and so only a brief discussion is given here. Figure 11.1 shows the layout. The system comprises mainly 12 large vacuum chambers, separated by 12 short bellows adapter sections.

A simplified FEA model of a large vacuum chamber is shown in Figure 11.2, depicting the top plate and the contains 15 grooves for mounting the NMR probes. The 15 grooves on the bottom and flange ports are not shown. The FEA model predicts that the top and bottom surfaces deflect by 0.453 mm under vacuum load[2]. This is in agreement with the measurement of 0.45 mm[7]. The FEA model reconfirms that the chamber has a safety factor of 2.9, and the wall stresses are below 12000 psi, as required by the ASME Pressure Vessel Code for pressure vessels for Aluminum 6061-T6.

The 12 vacuum chambers and 12 bellow adapter sections are bolted together and placed in between the upper and lower pole pieces. The average radius of this structure is mechanically fixed and cannot be adjusted. In the E821 design, the vacuum chambers are electrically connected to one another via bolting hardware, except at a single location where there is a thin dielectric sheet. This prevents eddy currents, such as arising from energy extraction of the magnet, from traveling completely around the ring. For E989, we will modify the electrical connections slightly as described below. Finally, all chamber materials including bolting hardware are non-magnetic.

Figures 11.3 and 11.4 show the cage system and how it resides inside a vacuum chamber. The cage system holds the quadrupole plates, kicker plates, and the rails used by the trolley.

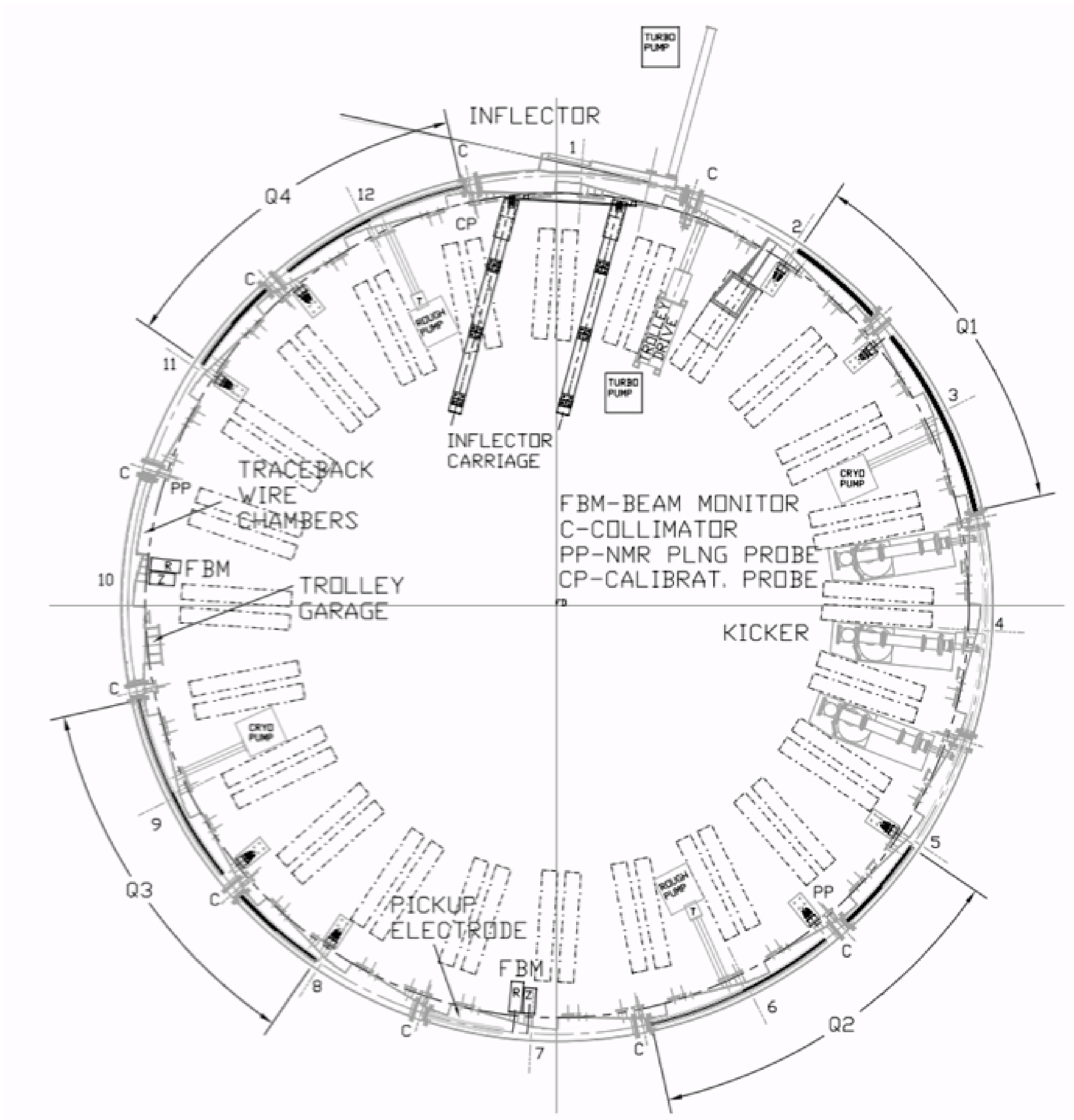

Figure 11.1: Layout of the BNL E821 beam vacuum chamber system.

Screws allow for adjusting the position of the cage within the vacuum chamber system. The position of the cage system plays an important role, and has the following requirements. (1) The rail system from neighboring vacuum sections must line up to allow smooth motion of the trolley as it travels between sections. And (2), since the quadrupole plates and kicker plates positions define the beam storage region, these devices should place the beam in the most uniform portion of the magnetic field. The beam center should be at the geometrical center between upper and lower pole faces. The E989 method to survey and align these cages are described in the following subsection.

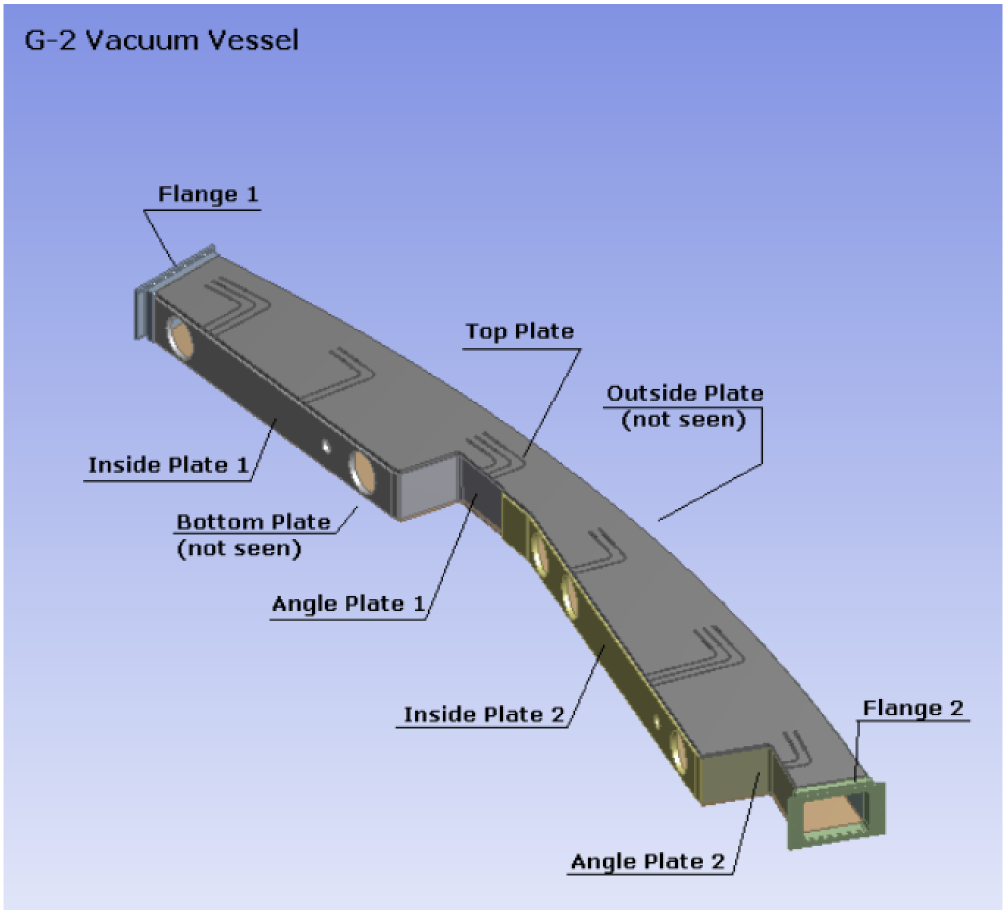

Figure 11.2: Simplified mechanical model for stress and strain analysis.

11.1 Changes to the E821 Design

For E989, we are proposing to make the following changes. For E821, the magnetic field gradient near the azimuthal boundary between two yokes was found to be sufficiently high, causing the fixed probes in that region to have readout difficulties. The reason for the higher gradients are discussed in chapter 9. For E989, while we expect to minimize the gradient with improved shimming, we will also lengthen or cut new grooves to optimize the probe placement. The maximum number of affected grooves are shown in reference [3].

In E821, the trace back system operated in air and was located in vacuum chamber sector 10, which was modified to be without a 'scallop'. For E989, a straw station will be in vacuum chamber 11, and vacuum chamber sector 10 will have its scallop shape reinstalled. Straw stations will also be placed in sectors 2 and 8. The inner radius vertical side walls of sectors 2, 8 and 11 will be modified to accept the straw chamber flange. Figure 19.5 shows the locations of the proposed changes.

Finally, the vertical inner radius surface of the vacuum chamber will be lined with insulation. This will improve the thermal stability of the magnet iron, which is critical for the field uniformity as discussed in Section 9.4.

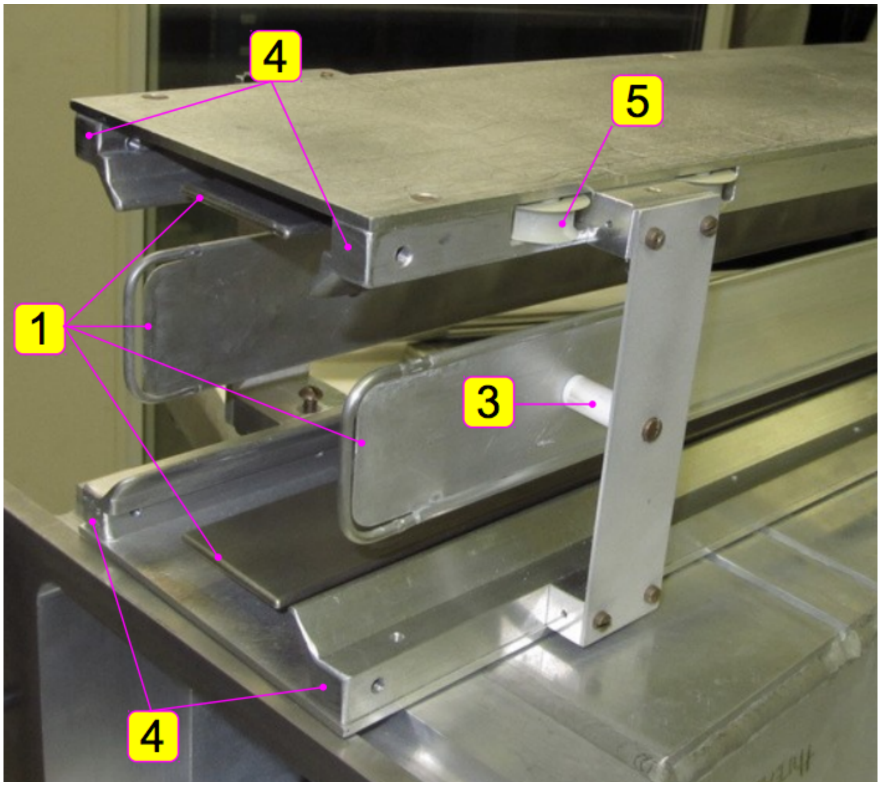

Figure 11.3: Picture of a cage system showing the (1) quadrupole plates, (3) macor (insulator) supports, (4) trolley rails, and (5) a wheel for guiding the cable that pulls the trolley

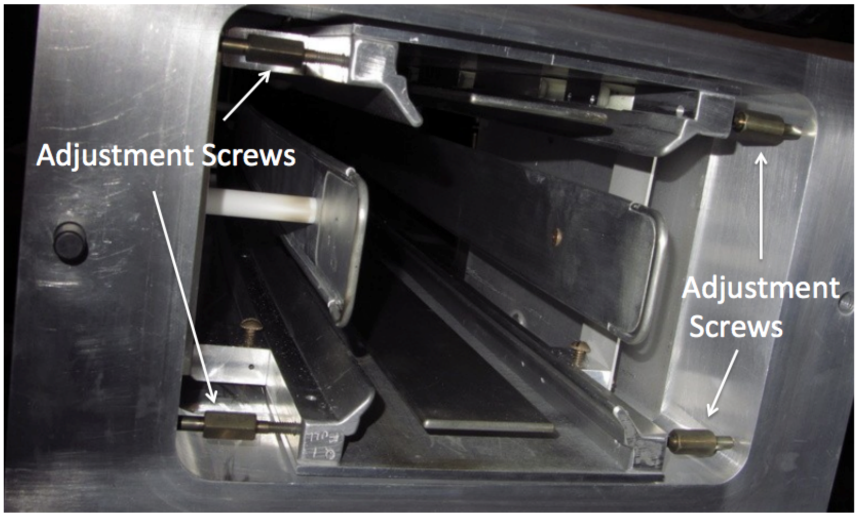

Figure 11.4: Picture of a cage system inside a vacuum chamber showing the adjustment screws to center the quadrupole plates with the geometrical center of the pole pieces.

11.2 Vacuum Chambers

This WBS refers to the actual chambers, the small bellows, the piping to the pumps, and the bolting hardware. We will be making major modifications to sectors 2, 8, 10, and 11.

This WBS also covers the reassembly labor effort.

Chamber sectors 2, 8 and 11 would be re-machined to accept the new in-vacuum straw trace back chambers. For sector 10, the ‘scallop’ portion must be reinstalled. The grooves housing the fixed probes in near the boundary between two yokes will be modified, allowing the affected probes to operate in a lower gradient region of the field.

11.2.1 Chamber Electrical Grounding

As discussed in chapter 9, each large metallic component will have a single low impedance connection to the star-shaped structure that defines the ring ground (“the star ground”). Since the bolts tying the chambers together present a high impedance at high frequencies, they cannot serve as a grounding path for the chambers to one another. Therefore, as shown in figure 11.5, each of the 12 large chambers will have a single dedicated low impendance connection to the star ground. In addition, we wish to cut the path of eddy currents circulating through all 12 chambers, which would arise from a magnet quench or energy extraction. Dielectric sheets will be inserted in between chamber flanges to increase the impedance for these eddy currents, which are at low frequencies.

Devices attached to the chambers, such as the NMR electronics hardware, straw chambers, kickers, and quads will typically be electrically isolated from the chambers. In particular, the vacuum pump ports will have ceramic breaks. Finally, there are G10 sheets on top and bottom of the chambers, isolating them from the poles.

11.2.2 Chamber Alignment

At Fermilab, the positions of all objects are given in terms of the DUSAF coordinate system. While the chamber positions do not need to be known to good accuracy, the trolley rails, which are mounted within the cages, need to be known to approximately 0.5 mm. Deviations from perfect rail alignment may couple with gradients in the magnetic field to change the field integral seen by the muons compared to that measured by the trolley. Assuming the goals of the shimming effort (Section 15.8) are met (in particular the azimuthal field uniformity) the corresponding error should be negligible for E989 [4]. Fiducial cups will be aluminum-welded to the inner radius of each chamber, and spherical reflectors will be periodically inserted into these cups. In combination with a laser tracker, the spherical reflectors allow for periodic monitoring of the position of each chamber in the DUSAF coordinate system. The position of the cages will be referenced to these fiducial cups. Therefore, the cage positions will be known in the DUSAF coordinate system.

A second and important in-vacuum cross-check will be made by the introduction of known, precise gradients in the magnetic field with the use of the surface correction coils. By tracking the NMR readings taken by the trolley probes throughout the ring in this dedicated run configuration, measurements of gradients different from that introduced by the surface coils would be indicative of cage misalignments.

11.3 Vacuum Pumps

The vacuum level must be less than 10^{-6} Torr in the region of the quadrupoles. This is to minimize the trapping of ionized electrons due to the residual gas. However, there is a vacuum load of $\sim 2.1 \times 10^{-5}$ Torr l/s from each of the two straw tracker trace back system [5]. From this requirement alone, the minimum pumping speed is 21 liters/sec at 10^{-6} Torr. However, each pump is attached to the vacuum chamber through a large pipe. As the pumps will likely contain ferromagnetic material and generate transients that would affect the magnetic field uniformity, they must remain sufficiently far from the vacuum volume. For E821, this distance was 1-2 meters. Therefore, extra piping will increase slightly the pumping speed requirement. Finally, the vacuum chamber system should remain clean, as the quadrupole and kicker plates carry high voltage and the high current, respectively. We will ensure this by utilizing dry (oil-free) roughing and turbo molecular pumps, and also cryogenic pumps.

We will utilize 5 Turbo Molecular Pumps (TMPs) at stations 6, 12, 10 (trolley drive), 8 (straw chamber), and 10 (near straw chamber) respectively. Each of these TMPs would be backed by a roughing pump. Cryogenic pumps will used on chambers 3 and 9. Detailed description of the pumps are given in the reference[6].

11.4 Mechanical Interface

As mentioned above, the vacuum chambers must provide the mechanical interface for several systems. This WBS covers the following activities needed for the NMR system:

- Modifications to the upper and lower grooves to improve the S/N of fixed probes near the boundary between yoke pieces.

- Calibration of the trolley position in DUSAF coordinates: for a given motor or position encoder reading, what is the actual position of the fiducial marks on the trolley in DUSAF coordinates.

- Calibration and operation of the plunge probe motors in chambers 10 and 1. Calibration refers to converting a given motor encoder reading to an actual position of the probe head.

There are two plunge probes, one integrated into chamber 1 and the other housed on top of a vacuum bellow that connects chambers 10 and 11. The mechanism to move the vacuum bellow plunge probe is shown in Figure 11.6. The probe itself is in air. The probe is moved radially by piezo electric motors. No changes are needed for the plunge probe mechanism, other than to upgrade the motor controller and computer.

The chamber 1 plunge probe mechanism moves radially as well as vertically. Therefore, the titanium vacuum bellow is significantly larger than the other (figure 11.6), and caused a noticeable shift in the absolute calibration. For E989, we plan to house the piezo motors and probe in vacuum, therefore bypassing the use of the large titanium below.

11.5 ES&H, Quality Assurance, Value Management, Risk

The vacuum chamber system should pose no health hazard, since the chambers, when evacuated, have a 2.9 safety factor for stress before yield. Quality assurance and value management concerns are minimal since we are reusing or modifying a few E821 chambers.

There is a risk that the new in-vacuum straw traceback chambers provide too much gas load to the vacuum. In that event, a corrective action could be to add additional pumping. This risk is addressed in the straw trace back discussion of this document.

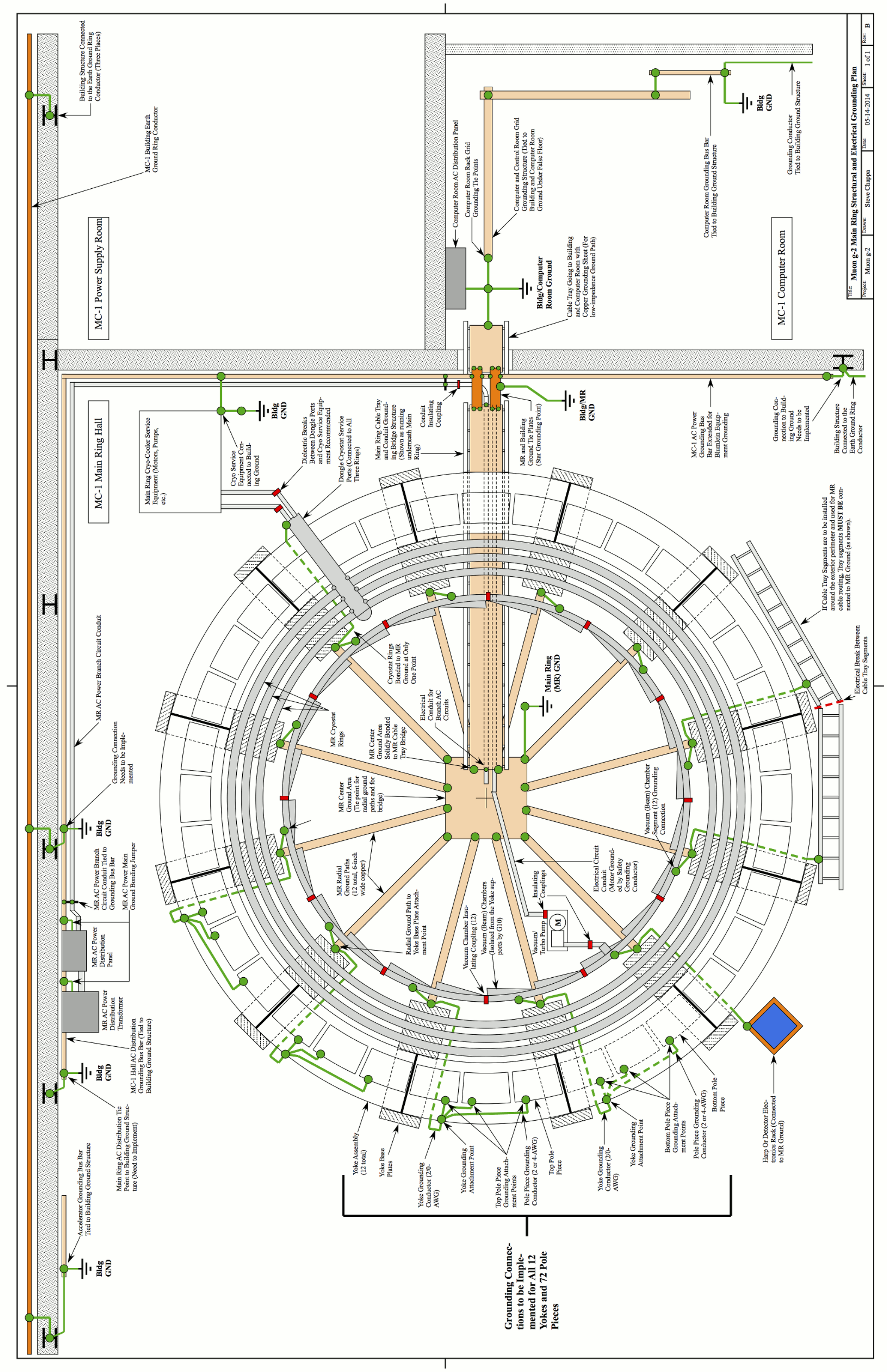

Figure 11.5: The grounding of g-2 metallic structures.

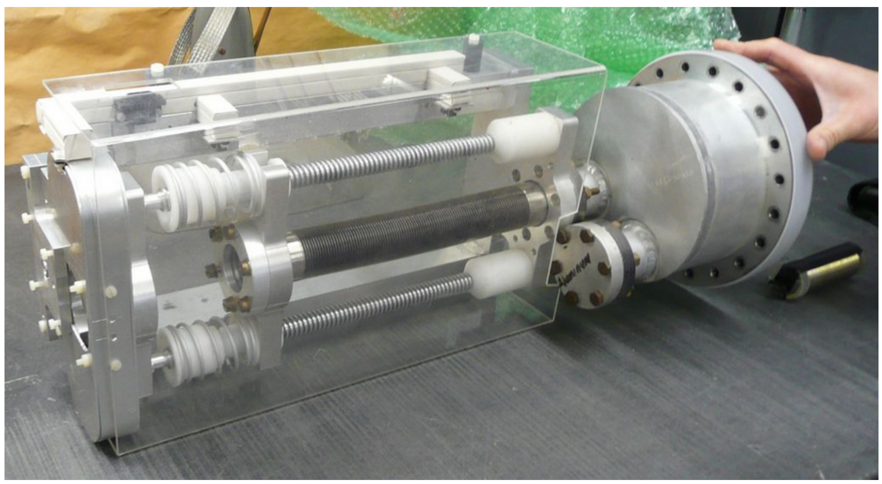

Figure 11.6: The plunge probe mechanism. The probe lies inside the titanium vacuum bellow.

References

[1] Design Report, BNL E821, A New Precision Measurement of the Muon $(g-2)$ Value at the level of 0.35 ppm. 3rd edition, D.H. Brown et al. B.L. Roberts Editor, March 1995.

[2] G-2 Vacuum Chamber FEA. g-2 DocDB note 417-v1.

[3] Fixed Probe Vacuum Chamber Modifications. g-2 DocDB note 1784.

[4] Transverse Trolley Position and Inflector Fringe Field 2001 Data. g-2 DocDB note 1852.

[5] Tracker Requirements. g-2 DocDB note 514-v1.

[6] Vacuum Pump System description for SR Vacuum Chambers. g-2 DocDB note 1832.

[7] H.C. Hseuh et al, E821 Muon $g-2$ Internal Note No. 248, 1(1995).