FNAL MAIN INJECTOR γ_t-JUMP SYSTEM BEAMTUBE DESIGN

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Abstract

The design of the FNAL Main Injector γ_t-jump system calls for a special beamtube that is to be placed inside the pulsed magnets. The requirements for this beamtube include: an elliptical shaped tube that mates with the existing vacuum system, high electrical resistivity for reducing the eddy current effects, high strength for withstanding the vacuum load, and a design that facilitates simple fabrication and installation. Inconel 718 was selected to meet these criteria. Results obtained from analytical calculations, 2-D and 3-D finite element modeling, and testing of prototypes were in general agreement. The design process, analysis results, and final specifications are discussed.

1 INTRODUCTION

The pulsed magnets in existing γ_t-jump systems have typically contained round beamtubes made of ceramic materials. This type of beamtube is used because of the unique requirements of a γ_t-jump system [1], which include: a high electrical resistivity to minimize eddy current effects, high strength to withstand the vacuum load, and the need to mate with the existing vacuum system. The FNAL Main Injector (MI) vacuum system consists of a stainless steel 316L beamtube with a somewhat elliptical shape. Because of the shape of the MI beamtube, using a round (ceramic) beamtube for the γ_t-jump magnets would introduce significant transition problems in the system. As a result, an effort was made to develop a metal beamtube with an elliptical cross-section that satisfied all the necessary requirements of the γ_t-jump system. In addition to solving the transition problems, such a design would also simplify the fabrication and installation processes.

Based on the Main Injector γ_t-jump system requirements described above, a metal (Inconel 718) beamtube with an elliptical cross-section has been developed. Data from analytical calculations, 2-D and 3-D finite element modeling, and measurements of prototypes were used in the development of the final design.

2 DESIGN PROCESS

2.1 Material Selection

Of all the materials available for use in fabricating the MI γ_t-jump system beamtube, one material was found that seemed ideally suited to meet all the necessary requirements, Inconel 718. The properties that make this material attractive for this application include its: high electrical resistivity, good machineability and weldability, and high mechanical strength. Figure 1 provides a comparison of selected material properties for Inconel 718 and stainless steel 316L.

Property	Inconel 718	S.S. 316L
Electrical Resistivity (ρ) ($\mu\Omega$-cm)	125	73
Tension Modulus (E) (psi)	29.8×10^6	28.0×10^6
Poisson's Ratio (ν)	0.284	0.290
Yield Strength (ksi)	150 - 220	35
Ultimate Strength (ksi)	180 - 230	80

Figure 1: Selected material properties of Inconel 718 and stainless steel 316L.

2.2 Eddy Current Effects

Eddy current effects have a negative impact on the field inside the beamtube. The extent of these effects is directly proportional to the conductivity of the beamtube. As a result, it is preferable to use a beamtube with a low conductivity. The conductivity of an elliptical beamtube can be approximated using the following equation:

$$\gamma = (1/\rho) \times t$$

where (γ) is the conductivity in $\mu\Omega^{-1}$, (ρ) is the resistivity in $\mu\Omega$-cm, and (t) is the thickness in cm. The beamtube used in the Main Injector accelerator is made of stainless steel 316L and has a wall thickness of 0.060" (0.152 cm). Using the above equation, the conductivity of the existing MI beamtube is 0.002 $\mu\Omega^{-1}$. Whereas, the conductivity for a 0.025" (0.064 cm) thick beamtube made of Inconel 718 is 0.0005 $\mu\Omega^{-1}$. By using a thin Inconel beamtube for the γ_t-jump system magnets, the conductivity can be reduced by a factor of four. For a detailed discussion of the eddy current effects of a beamtube in a pulsed magnet, see [2].

2.3 Mechanical Analysis

Once a suitable material had been found, the next step in the design process was to study the mechanical characteristics associated with various geometries of elliptical beamtubes made from Inconel 718. Analytical calculations [3] were used to model the effects (deflections and stresses) an external vacuum load of 14.7 psi (1 atm)

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would have on various sized elliptical beamtubes. Three equations were used for these calculations:

$$|\sigma_2|_{max} = \left|\frac{6K_2 pa^2}{t^2}\right| + \left|\frac{pa}{t}\right|$$

$$\delta_y = 2C_1\left(\frac{pa^4}{D}\right)$$

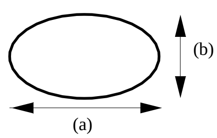
$$\delta_x = 2C_2\left(\frac{pa^4}{D}\right)$$

where (σ_2) is the maximum stress, (δ_y) and (δ_x) are the maximum vertical and horizontal deflections, respectively, (p) is the internal pressure, (a) is half the major diameter, (t) is the wall thickness, (D) is the flexural rigidity, and (C_1), (C_2), and (K_2) are geometry dependent functions of the ellipse being studied (see [3] for values of C_1, C_2, and K_2).

The goal of these calculations was to find a geometry that would deform, under vacuum, to the vertical aperture of the MI beamtube, while not exceeding the maximum allowable bending stress of the material, [0.6 x (yield strength)]. The following values were used in the above equations for this analysis: p = -14.7 psi, a = 1.950", t = 0.025", D = 42.2 in-lb., C_1 = 0.0407, C_2 = 0.0248, and K_2 = 0.166.

Once a desirable geometry was found, a 2-D finite element model was created, using ANSYS, to verify the analytical calculations and confirm the feasibility of such a design. The ANSYS results agreed (within an acceptable error) with the analytical calculations and were within the acceptable limits (see Figure 2).

Material: Inconel 718
Wall Thickness: 0.025"
Major Diameter (a): 3.90"
Minor Diameter (b): 2.50"
Internal Pressure: -14.7 psi



Results	Analytical	ANSYS (2-D)
Maximum Stress	90,223 psi	87,799 psi
Vertical Deflection	-0.410"	-0.442"
Horizontal Deflection	0.250"	0.269"

Figure 2: Analytical and (2-D) finite element results of elliptical beamtube under vacuum load.

2.4 Fabrication of Prototypes

Based on the results of the analytical and 2-D ANSYS calculations, prototype beamtubes were fabricated for testing. The material used to make the prototypes was 0.025" thick, Inconel 718. Three 36" long pieces of material were cut to size and rolled into round tubes. Two of these 36" long tubes were made to achieve the cross-section used in the analytical calculations. The third tube was made to a slightly larger cross-section. The round tubes were then electron-beam welded along their length. After welding, the prototype tubes were vacuum leak checked to ensure the quality of the weld. The round tubes were then cut into 18" lengths and pressed into the desired elliptical shape using a device developed at Fermilab. Once the desired elliptical shape was achieved, the tubes were annealed and age-hardened. The annealing process relieves any stresses that may have developed from welding and forming the material. The age-hardening process gives the material the high mechanical strength required to withstand the vacuum loads placed on it.

2.5 Testing of Prototypes

The deflections, under vacuum, of the 18" long prototypes were measured to test the validity of the analytical calculations and to see if the design would work. All the prototypes deflected significantly less than the calculations had predicted. These results raised some questions as to the validity of the models used. As a result, all the variables used in the models were verified. The exact thickness of the material was checked, the material properties of the prototypes were experimentally confirmed, and the model was redone using the exact geometry of the actual prototypes. None of these tests uncovered any significant variations from the data used in the original model.

The only other possibility was that because of the short length of the prototypes (18"), end effects from the vacuum-test setup were affecting the results. Because the analytical and 2-D finite element models assume an infinitely long tube, end effects are not taken into consideration. To account for these end effects, a 3-D ANSYS model was created. This model consisted of an 18" long beamtube, having the same geometry and end constraints as the test setup. The results of the 3-D model agreed (within an acceptable error) with the measurements of the prototype (see Figure 3). These results confirmed that the end effects do play a significant role in the amount of deflection of the beamtube.

Major Diameter (a): 4.289"
Minor Diameter (b): 2.846"

Results	(3-D) ANSYS	Test Measurements
Maximum Stress	41,400 psi	Not Measurable
Vertical Deflection	-0.231"	-0.242"
Horizontal Deflection	0.139"	0.132"

Figure 3: Prototype measurements and (3-D) finite element results of elliptical beamtube under vacuum load.

2.6 Transition Flanges

Because Inconel 718 can be welded directly to stainless steel, the connection of the γ_t beamtube to the existing Main Injector beamtube can be easily accomplished using a minimum amount of space. Thin (1/8") metal flanges could be welded to each end of the mating tubes. These flanges can then be welded together, creating a vacuum tight connection.

A set of Inconel flanges, that matched the elliptical profile of the prototype beamtube, was fabricated and welded to each end of the γ_t beamtube. (During the welding process, it is critical that the material is clean and an argon purge used to prevent any oxidation of the welded surfaces.)

The final step in the design of the prototype was to ensure that the Inconel to stainless steel connection could be made and that the resulting system would be vacuum tight. To verify this, two stainless steel blank flanges (one with a pump-out port) were fabricated and welded to the Inconel flanges. The same welding procedure was followed as before. The prototype beamtube was vacuum leak checked to 1.6 x 10^{-10} mm Hg (torr) and the deflections measured. No leaks were detected in the system and the measured deflections agreed (within an acceptable error) with the 3-D ANSYS model (modified to incorporate the flanges) results (see Figure 4).

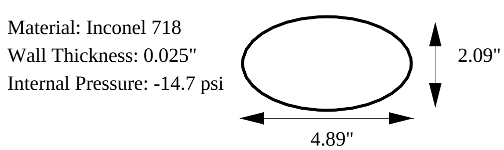
Major Diameter (a): 4.289"
Minor Diameter (b): 2.846"

Results	(3-D) ANSYS	Test Measurements
Maximum Stress	51,460 psi	Not Measurable
Vertical Deflection	-0.143"	-0.169"
Horizontal Deflection	0.092"	0.100"

Figure 4: Prototype measurements and (3-D) finite element results of elliptical beamtube (with flanges) under vacuum load.

3 FINAL DESIGN

The last step in the design process was to determine the final geometry for the γ_t beamtube, so that it mates properly with the existing Main Injector beamtube. Because all the measured data of the prototypes agreed very closely with the results of the 3-D ANSYS model, it was assumed that if the 3-D ANSYS model was modified to the correct final geometry, these results could be used for the final design. By making this assumption, the need to fabricate a final prototype to these exact dimensions would be eliminated. The ANSYS results showing the calculated geometry, deflections, and stresses of the final design of the FNAL Main Injector γ_t-jump system beamtube are shown in Figure 5.



Results	(3-D) ANSYS
Maximum Stress	62,210 psi
Vertical Deflection	-0.156"
Horizontal Deflection	0.063"

Figure 5: Geometry and finite element results of final Main Injector γ_t beamtube design.

The maximum stress (62,210 psi) for this design is well below the allowable bending stress [(0.6)(yield strength) = 90,000 psi] for Inconel 718 and the deflections are acceptable. An isometric drawing of the final design for the FNAL Main Injector γ_t-jump system beamtube is shown in Figure 6.

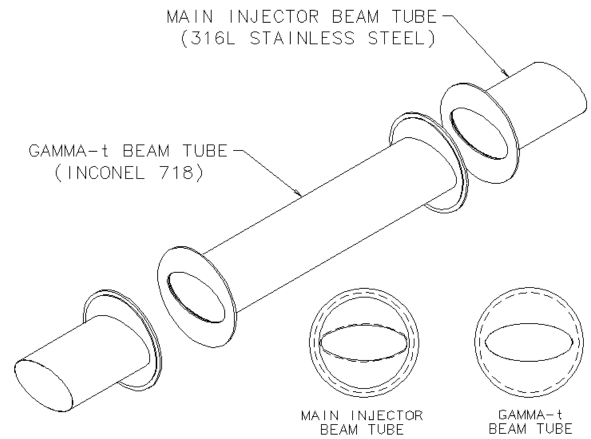


Figure 6: Isometric drawing of FNAL Main Injector γ_t-jump system beamtube design.

4 CONCLUSION

Based on the work described above, the design of an elliptical beamtube, made from Inconel 718, for the FNAL Main Injector γ_t-jump system seems to be a feasible alternative to the traditional ceramic design. In addition to meeting all the required design parameters, this design also provides for easy fabrication and installation with the existing Main Injector vacuum system.

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