

## METALLIZED CERAMIC VACUUM PIPE FOR PARTICLE BEAMS

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### ABSTRACT

A ceramic vacuum chamber segment in the form of a long pipe of rectangular cross section has been assembled from standard shapes of alumina ceramic using glass bonding techniques. Prior to final glass bonding, the internal walls of the pipe are metallized using microelectronic industry thick and thin film and electroplating technology. These advanced processes allow for precision patterning and conductivity control of surface conducting films. The ability to lay down both longitudinal and transverse conductor patterns separated by insulating layers of glass give the accelerator designer considerable freedom in tailoring longitudinal and transverse beam pipe impedances. Assembly techniques of these beam pipes are followed through two iterations of semi-scale pipe sections made using candidate materials and processes. These demonstrated the feasibility of the concepts and provided parts for electrical characterization and for further refinement of the approach. In a parallel effort, a variety of materials, joining processes and assembly procedures have been tried to assure flexibility and reliability in the construction of 10-meter long sections to any required specifications.

### 1.0 INTRODUCTION

The use of a ceramic vacuum chamber/beam pipe for the Los Alamos Advanced Hadron Facility has many potential advantages. The primary advantage of a ceramic vacuum chamber over a metal chamber is that ceramic avoids the eddy-current heating and eddy-current magnetic field distortion caused by the rapidly cycling guide field. The inside surface of the ceramic chamber needs to be metallized or otherwise made conducting in order to avoid the build-up of static charge. Furthermore, one needs a low impedance path (3 milli Ohms/meter) for the high-frequency image currents necessary for beam stabilization. These design considerations led Los Alamos to the preliminary design shown in Figure 1.1.

The vacuum beam pipe requirements for the Advanced Hadron Facility provides a unique challenge in its fabrication. The proposed design was to use high alumina (96%) ceramic extruded tubular segments which were joined end-to-end to form a 10-meter long ceramic vacuum chamber. On the outside of this pipe, alternate layers of conducting stripes and insulating glass were built up to provide the appropriate longitudinal and transverse impedances. In this way, the impedances of the pipe at various frequencies can be tailored to provide for effective beam stabilization and steering. A thin film of metal would also be coated on the inside of the beam pipe to provide a conductive inner surface. The ceramic beam pipe must be bakable to achieve  $10^{-9}$  torr pressure. In order to obtain the highest guide field magnetic flux within the beam pipe at the lowest possible magnet current, it would be desirable to have the clearance between the magnet poles and the beam pipe minimized. Having precision flat upper and lower surfaces over the entire 10-meter length of the beam pipe will reduce steering magnet power requirements.

Blending the accelerator designer's requirements with advanced ceramic processing and metallizing techniques has resulted in a new pipe design which has two major advantages: 1) the longitudinal stripes which provide beam stability have been moved to the inside of the chamber so they now serve as both beam stabilizers and static charge preventers, and 2) the ceramic pipe's upper and lower surfaces can be fabricated to be planar and parallel over the entire 10-meter length allowing a tighter fit within the steering magnet poles. The first pipe was made from machineable ceramic. It was anticipated that its higher cost would be offset by lower machining costs (compared to diamond grinding of alumina) to produce complex high tolerance pipe shapes in large quantities. The completed demonstration pipe section is shown in Figure 1.2. The glass cover allows the internal stripes to be seen. All the ceramic joints are sealed with a vitreous glass applied in tape form, then fired. The silver stripes are standard thick film silver pastes applied by "doctor blading" rather than screen printing and fired using standard temperature profiles.

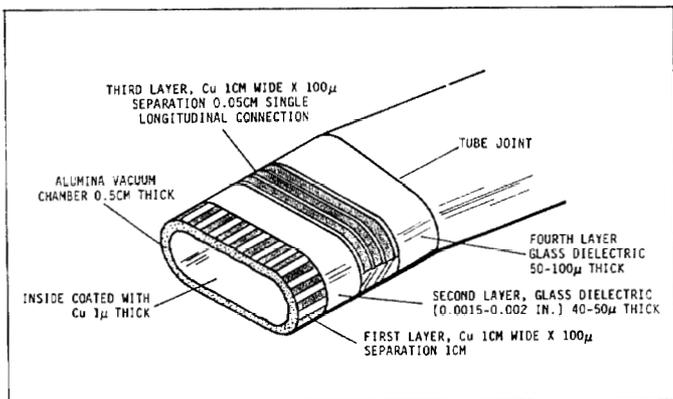


Figure 1.1 Original Dipole-Magnet Vacuum Pipe Design

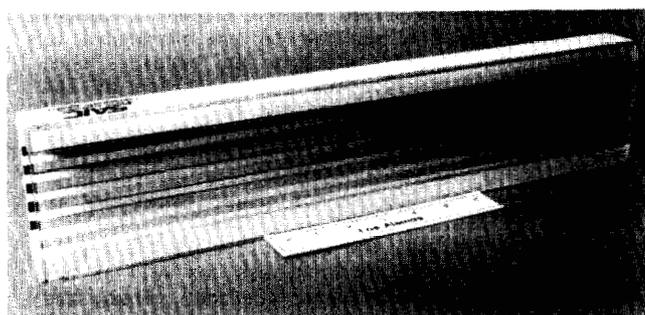


Figure 1.2 Completed First Iteration Demonstration Pipe (with Glass Cover)

The second pipe and a "control" pipe were made for impedance measurements and to improve on the first pipe. It was found that alumina can be economically made in curved complex shapes using precision sagger techniques to provide very flat upper and lower surfaces for insertion into the magnet. Making the pipe in two "C" sections also minimized the number of joints and sealing surfaces required. They can be manufactured as arch segments with a typical 20-meter radius of curvature and be joined at the inner and outer mid-plane by a fused glass seal. This design allows the transverse joints in the beam pipe to be staggered such that greater overall pipe alignment and durability can be achieved. The conductors can be easily placed on the inner surface of the pipe halves and the appropriate pattern built-up to achieve desired longitudinal and transverse impedance. The optimization of this type of design has proceeded in two directions. First, structural analysis of the ceramic pipe and bond strength were performed to ensure that the pipe will provide the strengths and stiffness required. Secondly, development of the conductor/insulator alternating layer system was accomplished to determine the types of micro-electronic fabrication and firing technologies which are required to fabricate the impedance matching stripe system. Figure 1.3 shows the as-fired one-half sections with the conduction stripes applied.

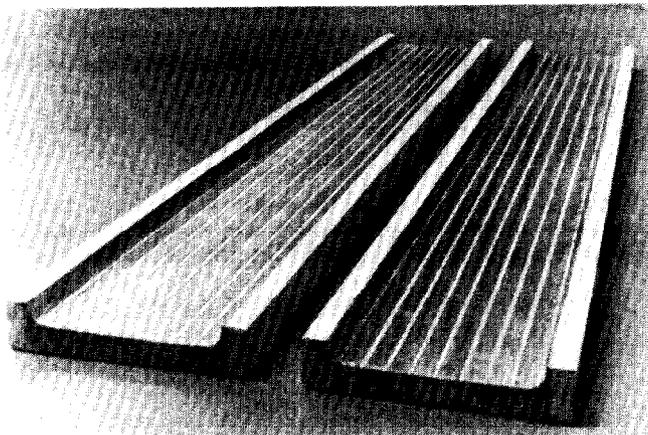


Figure 1.3 As-Fired Second Iteration Demonstration Pipe Sections

## 1.2 Ceramic Pipe Design and Analysis

The stress state in the ceramic pipe joints and conductor stripe system have been evaluated using the Algor/SUPERSAP finite element computer program. The load applied to the structure is primarily atmospheric pressure and bending loads applied during fabrication and insertion of the vacuum chamber into the magnet poles. The wall thickness of the upper and lower surfaces of the ceramic pipe are critical. A thinner wall allows the magnets to be placed closer to the beam thereby lowering the magnet power necessary to achieve the desired field strengths. As the wall thickness decreases, the deflection of the pipe's top and bottom surfaces increases, as well as the tensile stress on the inner surface. Thus, the

finite element computer programs have been used to optimize the wall thickness with respect to lateral dimension. Stresses and deformations of the ceramic pipe have been calculated by finite element methods and confirmed by theoretical calculations. At present, the pipe wall thickness selected is 6.35-mm (.25-inches). At this thickness, the maximum stress expected is 27.5 MPa (4,000 psi), and the maximum deformation is .12 mm ( $4.69 \times 10^{-3}$  inches), both at the center of the top or bottom of the pipe. Computer models have shown that the pipe could be made with top and bottom of wall thickness 2.5-mm (0.10-inch) and still maintain a safety factor of 2 for vacuum loading. In this case, the maximum stress is 130 MPa (19,000 psi) and maximum deformation is 1.0 mm (.039-inch).

An analysis of the stresses in the ceramic glass bond has been made. By placing the major bond between the two halves at the mid-plane, it is subjected to mainly shear due to pipe bending. Since this bond has a large cross-sectional area resisting shear, stresses of less than 6.8 MPa (1,000 psi) are developed. The tensile stresses in the ceramic-to-ceramic glass bonded butt joints are also low due to the fact that they are thin joints, and the glass has a modulus one-quarter that of the alumina. Tensile stresses that are 6.8 MPa (1,000 psi) are expected, under the worst case of bending, without vacuum. With the pipe under vacuum, the butt joints are all under compressive loading which makes the pipe less susceptible to fracture. The structural analysis has shown this concept is under relatively low stress compared to the material strengths and should be very robust and a structure which can be handled easily. The ceramic beam line at Rutherford, England was reported to be both easy to handle and resistant to failure.

Stresses in the silver stripes have been analyzed in two ways. First, the stress in the silver, due to the bending stress in the ceramic, has been analyzed. As the silver is much less stiff than the ceramic, the stress under the same deformation is much lower. It was found that the stress in the silver due to vacuum loading on the ceramic was 5.5 MPa (800 psi). The second method was thermal stress analysis. If the silver stripes are applied at a high temperature, high tensile stresses and longitudinal yielding in the silver would occur during cooldown. This is due to the mismatch in thermal expansion coefficients of the silver and alumina. The thermal stresses can be reduced by annealing during cooldown. Furthermore, by adding a chill phase to the cooldown (about  $-100^{\circ}\text{F}$ ) thermal stress could be brought to zero at room temperature. Currently, the same finite element program is being used to evaluate the stresses in the silver and glass alternating layers which compose the conductor sandwich. This program determines the stress and strain levels in these layers and compares it to fracture stress to predict microfracture in the glass insulators and yielding of the silver conducting stripes which would cause the conductors to break and go open circuit after repeated thermal cycling.

### 1.3 Conductor Fabrication

The microelectronics industry has developed a system of utilizing precious metal pastes and dielectric pastes to produce high reliability hybrid circuits in hermetic packages. These pastes are fired on ceramic substrates to form circuitry for silicon chips similar to a printed circuit board. The pastes are usually applied by screen printing. The metal forms conductor traces, capacitor plates, or bonding pads for the chips, the dielectric insulates the conductors and allows several stacks of conductors to be used to conserve space or form crossovers. The use of precious metals takes advantage of their high conductivity and their ability to be sintered (fired) in air, which is also the preferred firing medium for glasses.

The scale of the pipe fabrication far exceeds the size of most hybrid substrates (usually just a few square centimeters in area) and the shape of the pipe adds to the complexity of applying the pastes. However, this technology, with modifications, was applied as a basis to the fabrication of the pipe assembly.

The requirement for high electrical conductivity in the stripes narrows the material selection to copper and silver. Ideally, solid annealed pure metal stripes would provide the required conductivity with the smallest cross-section. Applying bulk metal stripes would be difficult. Electroplating is easier to accomplish, but the resulting stripes have a slightly lower conductivity than the bulk material. Neither silver nor copper adhere well to ceramics or glass directly. Metal to ceramic bonding schemes are used extensively in micro-electronic thick film technology. These methods are particularly useful if the stripes require insulation by layers of glass as in the original multi-layer design. Silver is generally preferred over copper despite the material cost difference since it can be sintered (fired) in air without the oxidation problems associated with copper.

Most off-the-shelf silver thick film pastes intended for microelectronics use are mixed with glass powder (for adhesion to ceramic) and alloying elements to prevent leaching or migration. Alloying always reduces the conductivity of silver (and all pure metals) as do the entrapped glass particles and voids inherent in the fired film. The glass and voids do, however, provide adhesion sites for the dielectric coatings. These fired thick films are also poor substrates for subsequent deposition of an electroplated layer. (Firing temperatures of 850°C are usually required for fabrication).

The removal of organics from the paste during firing limits the resultant fired thickness. This would necessitate several cycles to build up the required conductivity. A silver paste with these limitations was used for the first pipe. This was satisfactory for a demonstration piece of hardware. For the electrical testing to be done on the second pipe and for the final article a more compatible dense silver and pin-hole-free dielectric paste combination was developed. The

silver paste is suitable for use as a full thickness stripe or as a substrate for electroplating. This system would be ideal for (and necessary for) the multi-layer design in Figure 1.1. In order to produce the beam pipe sections in time for impedance testing, a simpler alternative approach was used. For these tests, it was not necessary to produce end-to-end joints or to join the pipe halves with a glass seal, although the techniques for this procedure have been developed and successfully demonstrated using both high-strength devitrifying glasses and vitreous glasses which permit reflow and rework.

A silver resinate (organometallic) was used to form a pure metallic thin film base for electroplating. The ceramic was masked to define the stripe pattern. The resinate solution was applied uniformly over the areas to be metallized by a spray technique. After drying, the part was slowly heated to 250°C. At this temperature, the resinate decomposed to pure elemental silver and had started to sinter into a homogeneous thin film. Adhesion is primarily mechanical but the film easily withstood a tape test for adhesion. Leads were then soldered to the film, and the parts were assembled in an electroplating fixture. Fifty microns (2 mils) of silver were electroplated using modified conventional techniques.

### 1.4 Summary and Conclusions

Initial investigations have shown that a ceramic Advanced Hadron Facility beam pipe can be fabricated out of easily formed top and bottom sections of high alumina (96%) ceramic which are metallized on the inner surface using advanced microcircuit metallization technologies. Since these ceramic sections are only available at present in 1 to 2-meter sections, joints are essential to make up the required 10-meter segments between pumping stations. Continuity of the silver stripes (on the inner surfaces) at the joints is of prime concern. This was accomplished on the first pipe and alternative approaches have been tried in keeping with our philosophy of making this system as versatile as possible. The ability to bring the stripes out to the external surfaces allows monitoring or bypassing of individual stripes. This same technique allows thick film "circuitry" to be built onto any of the pipe surfaces, on or under a stripe, for sensing purposes or for magnet coils at strategic locations.

The thermal cycling, outgassing, and bonding and structural behavior of these pipes have yet to be measured and will be part of a continuing program. The longitudinal and transverse impedance of model ceramic beam pipes of two feet in length and approximately half-scale dimensions in cross-section are being evaluated by Los Alamos National Laboratories to determine the actual longitudinal and transverse impedance and to determine how these properties can best be tailored to meet the needs of their Advanced Hadron Facility.