Fermilab Proton Driver
R&D Effort for Composite Vacuum Chamber

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Fermilab is currently exploring the possibility of building a new proton−accelerating machine, the Proton Driver. The Proton Driver has some unique technical challenges that must be overcome before further design and planning can continue. One of these issues is the dipole magnet vacuum chamber. Because of high magnetic fields typical metallic beam tubes experience extreme eddy current heating problems. The use of conventional materials to construct the vacuum chambers would require active water−cooling of the chambers. In an attempt to eliminate the additional cost and reliability issues associated with the cooling system Fermilab has decided to pursue an R&D effort to develop alternative chamber designs.

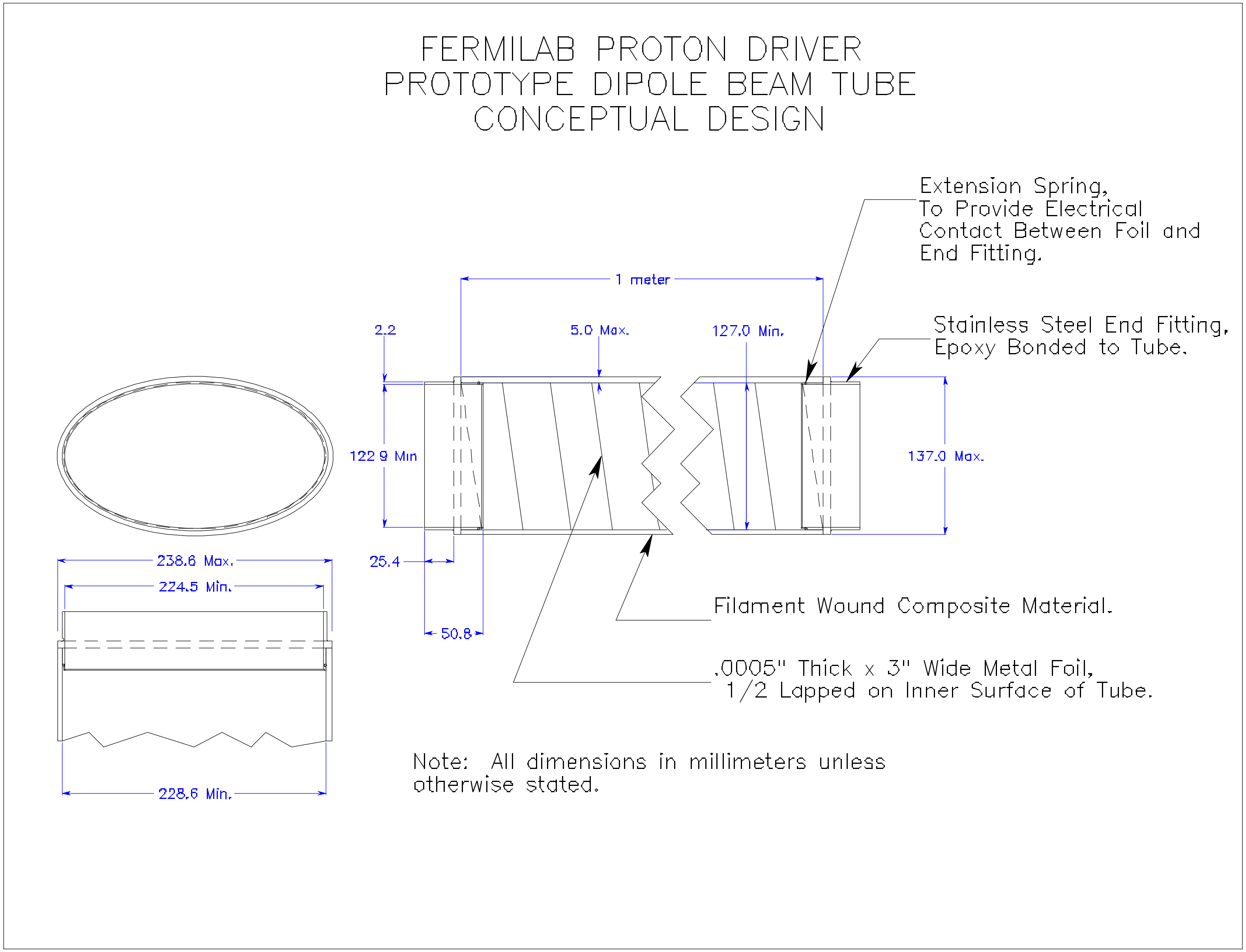
One of the alternatives is a chamber constructed of composite material with a thin metallic liner on the inner surface. There are many challenging issues associated with constructing a beam tube of this type. The assembly must be able to survive in a high radiation environment with a useful life expectancy of about ten years. Due to the metallic inner surface some eddy current heating will still be present and therefore an elevated operating temperature of about 200C is anticipated. Another major operating constraint is the vacuum quality inside the chamber. Machine operation requires that we maintain an average pressure of 10^{-8} torr inside the beam tube. This requires that the specific outgassing rate for the assembly be less than 10^{-10} torr−l/s−cm^2.

A similar vacuum chamber was constructed at CERN in Switzerland during the mid 1980’s. A paper on this chamber ("Vacuum Chambers in Composite Material", G. Engelmann, M. Genet, and W. Wahl) is contained in the July/August 1987 issue of the Journal of Vacuum Science Technology. Although CERN’s chamber is similar, the materials that they used will not work for our application. The electrical resistance of the carbon fiber and the aluminum foil that CERN used is too low to be used in our application. It is therefore necessary for us to explore the use of alternative materials.

The goal of this R&D effort is to produce a number of mechanical test samples and assemblies using various materials, fabrication techniques, and fabricators for technical evaluation by Fermilab technical staff. Small material samples can be used for mechanical, thermal, and radiation testing, but assemblies similar to the one shown below (fig. 1) will be needed for vacuum and ultimate lifetime testing.

Our preliminary investigation into composite vacuum chambers has identified a number of parameters that will drive material selection and some materials that may be acceptable for use in our chambers. The appendix of this note contains the findings of our preliminary investigation. Appendix A contains the basic parameters for the final design of the vacuum chamber. Appendix B contains a list of possible candidate materials for fabrication. Appendix C contains the results of a FEA simulation that we ran to study feasibility. Appendix D contains contact information for the various materials, suppliers, reference, and project personnel.

Fig. 1



FERMILAB PROTON DRIVER
PROTOTYPE DIPOLE BEAM TUBE
CONCEPTUAL DESIGN
Extension Spring, To Provide Electrical Contact Between Foil and End Fitting.
1 meter
2.2
5.0 Max.
127.0 Min.
Stainless Steel End Fitting, Epoxy Bonded to Tube.
122.9 Min
137.0 Max.
238.6 Max.
224.5 Min.
25.4
50.8
Filament Wound Composite Material.
.0005" Thick x 3" Wide Metal Foil, 1/2 Lapped on Inner Surface of Tube.
228.6 Min.
Note: All dimensions in millimeters unless otherwise stated.

Appendix A

Metal−Lined, Filament−Wound, Composite Tubular Vacuum Chambers for Particle Accelerator

Service Environment−

Fully evacuated (1 Bar internal vacuum)
High radiation: 400MeV − 16 GeV protons, plus some γ and neutrons
15Hz cycling 1.5T magnetic field, which generates
  ~ 170−190 Watt/meter of eddy−current dissipation in the tube in a non−uniform distribution
High temperatures / large temperature gradient around tube: From simulation, roughly
  T ~ 210C at major diameter
  T ~ 170C at minor diameter
High humidity: variable, up to 100% RH for extended periods

Production Unit Requirements−

Elliptical cross section, 22.86 cm major ID, 12.7 cm minor ID
Fabricate 6m long unit in one piece
  −some units must be curved (37.6m radius of curvature)
Able to withstand 2 bar pressure differential without implosion.
Total chamber wall thickness: < 5mm.
Maximum elastic deformation in minor axis in service: < 1mm (No Yielding)
Matrix and fiber must be electrically insulating
Liner must be thin (~25μm total) , high resistivity (> 120 μΩ−cm) metal (See Below)
Magnetic permeability of all materials must be less than 1.01 μ_0.
Thermal conductivity of finished composite as large as possible (> 0.3 W/m−K ?).
Vacuum leak rate and vacuum outgassing rate into interior < 10^{-10} Torr L/cm^2−s.
Radiation Tolerance: meet above specs after > 10^8 Rad
  (10+ Year Lifetime in 10MRad/Year environment).
CLTE of liner and composite must be similar.
Interior must tolerate surface cleaning for ultrahigh vacuum
  (Vapor degreasing, detergent wash, water rinse)

Liner Requirements−

Liner must be metallic to provide particle beam shielding and to carry beam image current, and impermeable to gas to improve vacuum quality. These considerations suggest increasing liner thickness. The large and rapidly varying magnetic fields, however, will induce large eddy currents, and thus heat, in the liner. The optimal liner must, therefore, be thicker than the minimum described in the scaling laws below, and as thick as permitted by thermal considerations of the composite. The liner must have a magnetic permeability less than 1.01 μ_0. A low yield strength and low coefficient of thermal expansion are required to prevent liner delamination from composite. Perhaps special processing (annealing) can be used to lower the yield strengths of some of the alloys under consideration. The liners we have considered are either a foil strip wound helically with 50% overlap around a mandrel, adhesive bonded or brazed to itself, then overwound with the resin−impregnated filament, or some means of plating the interior of a finished composite tube.
We are interested in evaluating any liner material or method that can meet the stated requirements.

Simulation and analysis have led to the following scaling laws for the liner:

P_l = Total heat load per meter of tube length in Watts/meter
d_{min} = Minimum liner thickness (from particle beam considerations), in meters
NOTE: The thickness should exceed this value as much as permitted by thermal considerations.
d = Actual liner thickness employed, in meters
ρ = Liner material resistivity, in Ω m
T_{max} = approximate maximum chamber temperature in service, in Celsius

$d_{min} = 13.2\ \rho$
$P_l = 8.1\ d/\rho + 1.82(10)^4\ \rho^{1/2}$
$T_{max} = 3.30\ P_l^{1/1.33} + 50$

As an example, with Ti 15−3−3−3 foil ($\rho = 148\ \mu\Omega$ cm $= 148*10^{-8}\Omega$ m), 12.7μm thick but wound with 50% overlap for a total liner thickness of 25.4μm:

$d_{min} = 13.2 * 148*10^{-8} = 19.5\mu m$
$P_l = 8.1\ (25.4*10^{-6})/148*10^{-8} + 1.82 * 10^4(148* 10^{-8})^{1/2} = 161$ W/m
$T_{max} = 3.30\ (161)^{1/1.33} + 50 = 200C$

Matrix Requirements−

Maintenance of high strength and modulus up to 220C is essential. Must be electrical insulator. Low vacuum outgassing rate is required. High radiation tolerance is required. Moderate thermal conductivity is desirable (~0.3 − 0.5 W/m−K).

Reinforcing Fiber Requirements−

High modulus/high strength, electrically insulating (resistivity > $10^6\ \mu\Omega$ cm) fiber with moderate thermal conductivity is required. Large coefficient of thermal expansion is required to prevent liner delamination. High radiation tolerance is required.

Appendix B

Candidate Materials

Liner Metals

<u>Titanium alloy foil</u>

Ti 15−3−3−3:	Electrical resistivity = 148 μΩ cm Magnetic permeability = "Non−magnetic" per manufacturer Yield strength, strip = 965 MPa CLTE = $9.4 * 10^{-6}$ / C Available in 12.7μm strip from Alloys International Inc
β−21S:	Electrical resistivity = 135 μΩ cm Magnetic permeability = "Non−magnetic" per manufacturer Yield strength, strip = ? CLTE = ? Available in 12.7μm strip from Alloys International Inc

<u>Nickel alloy foil</u>

Inconel 718:	Electrical resistivity = 121 μΩ cm Magnetic permeability < 1.002 Yield strength, strip, annealed & aged = 1.1GPa (150ksi) CLTE = $13 * 10^{-6}$ / C Available in 12.7μm strip from Alloys International Inc
Inconel 625:	Electrical resistivitiy = 129 μΩ cm Magnetic permeability = 1.0006 Yield strength, strip = 350MPa CLTE = $12.8 * 10^{-6}$ / C Available in 12.7μm strip from Alloys International Inc.
Evanohm S:	Electrical resistivity = 137 μΩ cm Magnetic permeability = "Non−magnetic" per manufacturer Yield strength, strip < 1.24GPa (180ksi) CLTE = $13 * 10^{-6}$ / C Available in strip >= 2.54μm thick from Hamilton Precision Metals, Inc.

<u>Low−temperature arc vapor deposition / Metallic spray</u>

Many alloys possible, but equipment access to tube interior may be problematic
125 μ inch (~3 μm) surface roughness is typical
Vapor Technologies Inc, Boulder CO
Hitemco, Bethpage NY

<u>Solvent Electroplating / Vacuum Plating / Sputtering</u>

Alloys?
Thickness?
Porosity?
Bond?

Composite Matrix Materials

High Performance Epoxy
Tetraglycidyl methylene dianiline with diaminodiphenyl sulfone curing agent
(TGMDA with DDS)

Glass Transition Temperature ~ 250C
Service Temperature, Dry > 250C
Tensile Modulus @27C = 3.72 GPa
@150C = 2.62 GPa
Tensile Strength @ 27C = 59 MPa
@150C = 45 MPa
Electrical Resistivity ~ 10^{20} µΩ cm
Thermal Conductivity ~ 0.3 − 0.6 W/m−K
CLTE ~ 30−60 * 10^{-6} /K
Radiation Tolerance (CERN Data typ.) > 10^{10} Rad in Fiberglass Composite
~10^{7} Rad unfilled resin

Other Thermoset Polymers
Hexcel F650 Bismaleimide Resin
Cytec−Fiberite PMR−15
Ciba−Geigy Matrimid 5292

Glass Transition Temperature (Matrimid 5292) > 273C
Heat Deflection Temperature (Matrimid 5292) = 273C
Tensile Modulus (Matrimid 5292) @ 27C = 4.27GPa
@204C = 2.02GPa
Tensile Strength (Matrimid 5292) @ 27C = 82.0MPa
@204C = 40.0MPa
Electrical Resistivity (Kapton) = 10^{21} µΩ cm
Thermal Conductivity (Kapton) = 0.6 W/m−K
CLTE (F650) ~ 49 * 10^{-6} /K
Radiation Tolerance (unfilled Kapton) > 10^{9} Rad

Composite Reinforcement Fibers

Glass Fiber
E − Glass

Tensile Modulus = 81.3 GPa
Tensile Strength = 3.44 GPa
Electrical Resistivity = 4 * 10^{23} µΩ cm
Thermal Conductivity = 1.3 W/m K
CLTE = 5.4 * 10^{-6} /K
Radiation Tolerance = Known Very Good
CHEAP!

S − Glass

Tensile Modulus = 88.9 GPa
Tensile Strength = 4.59 GPa
Electrical Resistivity = 9 * 10^{21} μΩ cm
Thermal Conductivity = 1 W/m−K
CLTE = 1.6 * 10^{-6} /K
Radiation Tolerance = Probably Very Good

<u>Boron Fiber</u>
Textron Systems Inc Boron Fiber
Tensile Modulus = 400 GPa
Tensile Strength = 3.6 GPa
Electrical Resistivity = 2−3 * 10^{12} μΩ cm with large uncertainty, per Mfr.
(Elemental Boron = 10^{12} μΩ cm,
Tungsten Wire Core = 5.65 μΩ cm,
Is Tungsten fully consumed?)
Thermal Conductivity = ?
CLTE = 4.9 * 10^{-6} /K
Radiation Tolerance = ?
MOST EXPENSIVE, monofilament (100μm), or prepreg tape available from Textron Systems.

<u>Silicon Carbide Fiber</u>
ECI Nicalon HVR
Tensile Modulus = 186 GPa
Tensile Strength = 2.62 GPa
Electrical Resistivity > 10^{12} μΩ cm
Thermal Conductivity ~ 1 W/m−K
CLTE = 3.9 * 10^{-6} /K
Radiation Tolerance = Probably Very Good
Engineered Ceramics Inc.

<u>Ceramic (Al_2O_3) Fiber</u>
3−M Nextel 610
Tensile Modulus = 373 GPa
Tensile Strength = 2.93 GPa
Electrical Resistivity = Insulator
Thermal Conductivity ~ 1W/m−K
CLTE = 7.9 * 10^{-6}/K
Radiation Tolerance = Probably Very Good

Appendix C

Simulations

Simulation Parameters−

HVR Nicalon Silicon Carbide reinforced generic epoxy composite 5mm thick
140 μΩ cm liner, 25.4 μm thick. (This generates 170W/m of heat (eddy plus image))
Composite thermal conductivity of 0.3W/m−K
Convective cooling (h = 0 at top and bottom, increasing to h = 1.31 $\Delta T^{0.33}$ W/m^2−K)
Composite mechanical properties generated by I−DEAS Laminates:

E_{xx} = 99GPa
E_{yy} = E_{zz} = 38GPa
G_{xy} = 13GPa
G_{yz} = G_{xz} = 10GPa
ν_{xy} = 0.2
ν_{yz} = ν_{xz} = 0.12.
Allowable tensile stress x = 577MPa
Allowable tensile stress y = 53MPa

Mechanical simulations used 1Bar vacuum forces
Mechanical simulations involved no y direction stress (x is hoop direction, y is axial)

Results−

Maximum temperature	203C
Maximum stress, x	53MPa
Minor axis deflection	1.5mm

The temperature is barely sensitive to material thermal conductivity in the range 0.3 W/m−K to 2 W/m−K, and barely sensitive to variations in wall thickness of a few millimeters. Increased thermal conductivity may enhance durability by reducing thermal distortion stresses.

The temperature is most sensitive to the convection cooling coefficient. The addition of fins or pins to the outer surface could make a significant difference in the operating temperature. Fluid dynamics simulations would greatly reduce uncertainties in these results.

The Handbook of Plastic Materials and Technology, Rubin, 1990, p. 865 lists the following preliminary data for 50% filament by volume SiC/Epoxy composite, uniaxial reinforcement.

	@RT	@127C
Tensile Strength	1600 MPa	1330 MPa
Tensile Modulus	230 GPa	230 GPa
Compressive Strength	2280 MPa	1620 MPa
Flexural Strength	2200 MPa	2210 MPa
Flexural Modulus	224 GPa	210 GPa
Interlaminar Shear	105 MPa	63 MPa

The modulus and strength are significantly higher than those generated by I−DEAS.

Appendix D

Contact Information

Project Personnel

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Liner Materials / Processes

Ti 15−3−3−3
Ti β−21S
Inconel 718

Inconel 625:	Alloys International Inc. 85−J South Hoffman Lane Islandia NY 11749 631 342 0043 (Russ)
Evanohm S:	Hamilton Precision Metals 1780 Rohrerstown Road Lancaster PA 17601 800 HPM 7065
Metal Spray:	Hitemco 160 Sweethollow Road Old Bethpage NY 11804 516 752 7882 (Larry Cohen)
LTAVD:	Vapor Technologies, Inc.

Boulder Tech Center
P.O. Box 11170
Boulder, Colorado 80301
303−652−8500
(Mike Reilly)

Matrices:

Matrimid 5292:	Ciba Specialty Chemicals Performance Polymers 281 Fields Lane Brewster NY 10509 800 222 1906
PMR−15 BMI:	Cytec−Fiberite Inc. 714 666 4390 (Rory Robertson)
F650 PI Resin:	Hexcel Inc. 101 East Ridge Drive Suite 102 Danbury CT 06810 203 798 8311 (Charles Dunbar)

Fibers

Nextel 610 Alumina:	3M Ceramic Fiber Products 3M Center, Bldg. 207−1S−23 St. Paul MN 55144 651 733 4013 (Tim Ginrich)
Nicalon HVR SiC:	Engineered Ceramics Inc. 801 483 3100 (Jay Curtis)
Boron:	Textron Systems Inc. 978 657 2954 (Tom Foltz)

Reference

CERN Accelerator Laboratory in Switzerland has performed some R&D on similar chambers.

G. Engelmann, M. Genet, and W. Wahl, Vacuum Chambers in Composite Material, *Journal of Vacuum Science and Technology A*, July/August 1987, Volume 5, Number 4, pp. 2337 − 2341