AN OVERVIEW OF HIGH VOLTAGE DIELECTRIC MATERIAL FOR TRAVELING WAVE KICKER MAGNET APPLICATION*

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Abstract

Pulsed high power fast kickers are being used to change beam trajectories in particle accelerators. The fast rise and fall time of pulse waveform demands a transmission line structure for the kicker deflector design. The ideal design will be parallel metal plates. However, it uses very long straight sections to achieve the required deflection. In accelerators with constrained straight sections, high permeability materials such as ferrite have to be used to gain deflection efficiency. The transmission line kicker magnet is also referred as traveling wave kicker magnet. Its construction is based on distributed L-C cells along the longitudinal direction. The magnetic cells and capacitive cells are interleaved to simulate the characteristic impedance of a transmission line to minimize pulse reflection, and provide adequate frequency bandwidth to transmit the kicker pulse with fast rise and fall time. The magnetic cells are usually made of ferrite ceramics, but the capacitive cells have been made with different materials. For traveling wave kickers with higher impedance, the parallel plate vacuum capacitor has been used in CERN and KEK design. Others have used ceramic capacitors, printed circuit boards, and high permittivity ceramics as the capacitive cell. The high dielectric material has the advantage of compactness for low impedance kicker magnet construction. It continues to be very attractive for future kicker magnet applications. The high voltage phenomena associated with high dielectric ceramic materials have been widely reported in many industrial application areas. Their implication in the traveling wave magnet application has to be well understood. In this presentation, the areas requiring further quantitative study will be outlined.

I. INTRODUCTION

High dielectric material research has been identified as one of the future directions for repetitive pulsed power systems. It's a high potential technology in which a substantial breakthrough can lead to orders-of-magnitude improvement of the pulsed power system. This technology has vital importance for defense systems as well as for modern accelerator systems. In our particular interest, we examine the issues related to application of high dielectric material in accelerator fast kicker magnet systems.

A fast kicker system is a typical repetitive pulsed power system ranging from a few pulses per day to multi-million pulses per day. It's a key system for particle beam injection/extraction to/from a particle accelerator. The basic principle of the kicker system is to create a pulsed electromagnetic field to deflect charged particles traveling though its field region. Very often, the pulse rise and fall time are in the order of few tens to hundreds of nano-second determined by the time spacing between adjacent beam bunches.

The kicker strength is the product of the field strength and the kicker longitudinal length. As the beam energy gets higher and higher for the new accelerator designs or upgrades, the required kicker strength also grows higher and higher. However, the kicker length is often restricted to a very short straight section length. Therefore, the field strength has to be substantially increased to match the demand. These in turn will require a higher voltage and higher current pulser as well as a higher hold off capability of the kicker magnet.

A fast kicker system usually consists of a high voltage modulator for pulse forming/energy storage, a transmission line for pulse delivering, and the kicker as beam deflecting device. Electrically, a kicker with a transmission line structure that matches the impedance of the transmission lines can minimize the pulse reflections. A transmission line kicker magnet is a multi-cell L-C network with discrete ferrite sections and capacitor sections alternately arranged along the longitudinal axis of the beam orbit. Its characteristic impedance is $\sqrt{\frac{L}{C}}$ in the first order approximation. The use of high permittivity dielectric material in transmission line magnets has the advantage of compact in size, and can lower the impedance of the magnet to ease the driver voltage requirement.

II. HISTORY

Various transmission line magnet designs have been implemented at particle accelerators around the world. In this section, the early development at CERN, FERMI, and SLAC will be reviewed.

A. CERN/TRIUMF Kicker Magnet Development

The design of the transmission line kicker magnet can be traced back to the early seventies at CERN. A nine-cell 15-ohm impedance full aperture kicker magnet used interleaved aluminum alloy plates to from capacitance, and vacuum as dielectric. In this design, the magnet resides in a vacuum chamber with relatively stable operating conditions. This type of design is commonly

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operated under 35 kV on kicker magnet. At CERN, similar designs range from 8.3 ohm to 30 ohm, operating from 20 kV to 40 kV, have been used for PSB, PS ring, LEAR, Antiproton Rings, Electron Positron Accumulator and SPS for beam injection, ejection, transfer, etc. It had become a popular choice and been adopted by other accelerator facilities such as KEK and TRIUMF (Figure 1.).

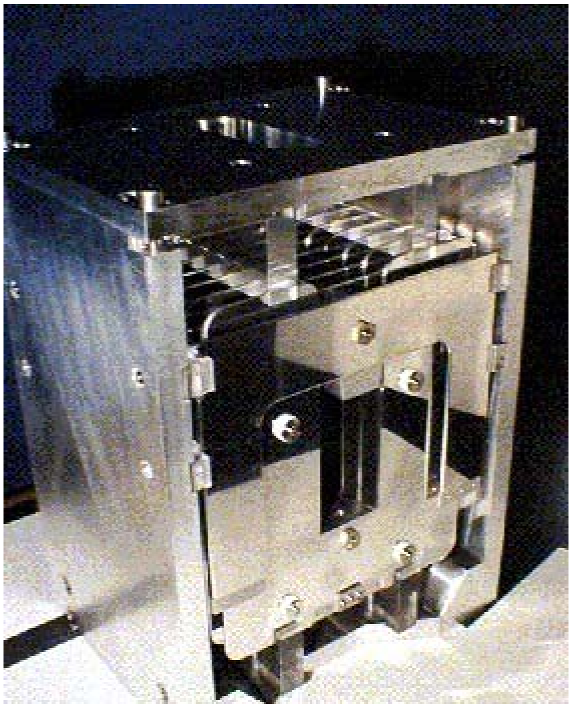

Figure 1. Prototype 30 Ω kicker magnet at TRIUMF based on the CERN PS design. Aperture 8cm x 16cm rise time 1% to 99% of 48ns, tested with 35kV pulses. The capacitor plate area would increase by a factor of 4 for a decrease in impedance by a factor of 2.

The aperture of the TRIUMF 10 cell kicker magnet is 8 cm x 16 cm. In tests with 35 kV pulses the rise time 1% to 99% was 48 ns. The capacitance (inductance) per cell is 65 pF (77 nH) and consists of parallel plate capacitors with a vacuum dielectric and 1cm spacing. The vacuum dielectric traveling wave kicker magnet requires very large area of metal plates to form the capacitance and is limited by the chamber size of the vacuum enclosure. Since the separation of the capacitor plates cannot be reduced the capacitor area must increase by a factor of 4 for a decrease in impedance by a factor of 2 (neglecting edge effects). It has been shown that it is feasible to build effective transmission line magnets with fast rise times using only 3 to 5 large cells but which require large capacitor values. It is impractical for lower impedance magnets or for magnets with larger cell inductances to use vacuum dielectric capacitors. With the space limitation at many accelerator facilities, the application of higher permittivity dielectric capacitor media is necessary.

B. FERMILAB Kicker Magnet Development

In the early nineties, Fermilab Tevatron antiproton injection kicker experimented with "six layer printed circuit boards which use a glass reinforced polyimide dielectric" as the capacitor section of the traveling wave magnet. The dielectric thickness is 0.09 inch per layer, rated at 1600 V/mil and operated at 25% stress level of its voltage breakdown rating. This magnet has 6.25-ohm impedance, and designed for 30 kV operation up to 10^7 pulse lifetimes. Different than the CERN design, this magnet is placed outside of the vacuum chamber. Development of this capacitor ended after several prototypes failed during pulse testing. The capacitors showed reasonable 60 Hz corona levels, but failed after a very short time in pulse testing at a similar voltage. The conclusion was that the glass fiber mesh could not be completely impregnated with the polyimide. Smaller mesh was considered, but the cost was higher than ceramic capacitors. A new design is described in Section III.

A 25 ohm traveling wave magnet design was adopted in the late nineties for FERMILAB Main Injector 8 GeV proton injection. In this design, the capacitors dielectric media is Grace Stycast 5952 Silicon potted between parallel plates. The dielectric constant of this material is 5.0. The maximum calculated voltage stress in the rubber is about 200 V/mil at 30 kV. The design lifetime is 10^8 pulses at 27 kV operating voltage and the system has about $2*10^7$ pulses at about 22 kV without failures. Both the Tevatron 150 GeV antiproton injection kicker and the 8 GeV proton injection kicker use cross coupling windings to improve the frequency response.

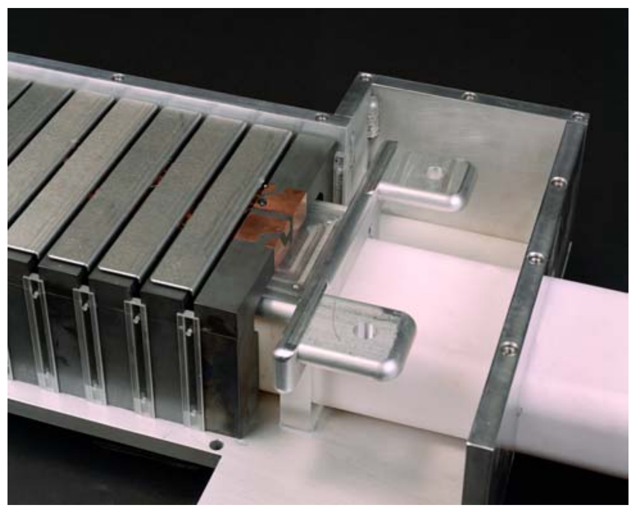

Figure 2. FERMI Main Injector Proton Injection Kicker Magnet

C. SLAC SLC Damping Ring Kicker Development

The Stanford Linear Accelerator required injection and extraction kicker for their Stanford linear Collider damping rings. The kicker could only be 40 cm long and produce a 8 mrad kick at 1.2 GeV which required 35 kV at 2 kA pulse with a rise and fall time of 60 ns. The South damping ring was used for cooling two positron bunches of which one bunch would be extracted at 120 Hz rate and be replaced with a new positron bunch. The next extraction and injection would remove and replace the other bunch. With a revolution time of 120 ns the rise and fall time of the kicker would need to be less than 60 ns. In 1981 it was believed by the designers that A "Slab ferrite magnet" would work like a transmission line if the capacitance per unit length and the capacitance per unit length would equal the characteristics of the drive cable. Ferrite blocks were stacked together to provide the desired capacitance and inductance. The Slab magnet did not work as a transmission type magnet because the magnetic field travels down the length of the magnet in the magnet gap at near the speed of light making it more like a lumped inductor with shunt capacitor then a transmission line. Only the gaps in the ferrite blocks provide any significant delay in the magnetic field. The Blumlein that drove the magnet had to be shorten to drive the magnet field off before it could reach a flat top to produce the required 60 ns rise and fall time. The magnets also electrically failed because the gaps between the ferrite slabs provide surface track, which eventually shorted the magnet.

Because the slab magnet was more of an inductor than a transmission line it was not suitable for the Electrons in the north-damping ring. The North-damping ring which was the same size as the south ring had two bunches of electrons which were both injected and extracted at the same time. The rise time of less than 60 ns for the extraction kicker was require and flat top of 120 ns to extract the second electron bunch. The fall time of the injector kicker needed to be less than 60 ns.

In 1985 Fermi Lab provide our second attempt at a transmission line magnet by use of large rings of ferrite incased in an aluminum case with a capacitance provided by a thin insulation between the ferrite case and the drive conductor.

The Fermi kicker magnet at first looked like a good transmission line magnet because the magnetic field did propagate down the magnet with a delay time of ~30 ns.

It also had flaws. The ferrite rings were large to provide for the capacitance from the grounded case to drive conductor. This meant that the permeability of the ferrite was an important part of the impedance matching of the magnet cells. The permeability of ferrite changes dramatically from low magnetic flux to operational magnetic flux. The result was that the magnet was never really impedance matched to the drive cables. This caused a reflection off the magnet and a rounding of the flat top pulse. In addition the thin insulation needed between drive conductor and grounded case failed under the radiation environment to which the magnet was subjected.

The final SLAC kicker magnet was an epoxy magnet build with small ferrite core to reduce the permeability effect and large plates to provide the capacitance. The magnet had a ceramic vacuum chamber which was coated with a conductor on the inside for beam impedance reasons. The tradition at SLAC is not to put ferrite of any organic in the vacuum chamber requiring the magnet to be outside the vacuum system.

The SLAC epoxy magnet with ferrite in cell with large are capacitor plates with thick epoxy insulation provided transmission line delay as the Fermi magnet had. However with the addition of the inside conductor coated ceramic chamber the additional capacitance changed the impedance match and well as adding dispersion in the magnet. The high voltage stress between the ceramic coating and the ferrite cell resulted in ceramic chamber fault. Breaks in the coating were need at both ends of the magnet to allow the magnet to operate.

Because of the way magnet fields propagate from one cell to the next in a ferrite magnet, the nonlinearly of ferrite and the addition of unwanted stray inductance and capacitate it is very difficult to develop a true transmission type magnet for fast rise time pulses.

III. NEW DEVELOPMENT

Commercial capacitors with high dielectric permittivity have been employed in various traveling wave kicker magnet designs. This design trend started at early nineties. In recent years, more and more designs are using the similar ideas with much more sophisticated fabrication techniques. Some recent results from FERMI, CERN, and KEK demonstrate that this method may achieve better reliability than the previous designs.

A. Argonne APS Injection Kicker Magnet

The Argonne Advanced Photon Source Injection kicker magnet design is the first one to use four ceramic capacitors interleaved with ferrite sections to form a traveling wave magnet. The impedance of each cell was design to be close to the characteristic impedance of the PFN that was made of coaxial cables. Since each half of the magnet had only four cells, it's far from being an ideal distributed-parameter magnet. The magnet would ring without proper damping. To overcome the ringing, each capacitor had a resistor connected in series. The resistor's resistance was equal to the PFN impedance. Although the resistors successfully damped the ringing, the rise time was slowed down somewhat as a side effect. During the test, it was found that there was magnetic coupling among magnet cells. The coupling significantly reduced the speed of the traveling waves. The magnetic coupling was caused by insufficient separation between cells. To improve the speed, the number of capacitors had to be adjusted.

A traveling wave kicker magnet has advantages of low characteristic impedance, fast speed, and lower PFN voltage requirement. However, it makes the magnet structure complicated, requiring very careful design to reduce the voltage stress. Such a magnet also requires frequent maintenance. Three traveling wave kicker magnets at the APS are installed in the positron accumulator ring that has no air conditioning and can be humid in the summer. Operating at a moderate voltage of 25 kV, the kicker magnets had frequent failures during early days of the operation, mostly due to corrosion around the electric connections and condensation on the surface. A maintenance program has been implemented in the last several years. Each magnet is cleaned and rebuilt at least once a year. This greatly reduced the frequency of failures. Most recent kicker failures are exclusively in the PFN cable terminations and the cable itself. With proper maintenance, these faults can also be minimized.

There are 30 ceramic capacitors in three kicker magnets. Twenty four capacitors are made by TDK, rated at 50 kV, and six are made by Sprague, rated at 40 kV. Three kickers have been pulsed more than 1.3×10^9 times in total after more than 7 years operation. There is only one capacitor failure so far. Some capacitors have been pulsed for more than 630×10^6 times and show no sign of any performance degradation. This indicates that the ceramic capacitors are reliable.

B. Fermilab Tevatron Antiproton Injection Kicker Magnet

The new traveling wave magnet designed for Fermi Tevatron antiproton injection has chose commercial ceramic capacitor as a suitable solution. The ceramic material used is strontium titinate with a temperature coefficient of 4700 ppm/C. This material was chosen after kicker magnets for the antiproton source built with barium titinate starting failing after about 10^8 shots. This old magnets were rebuilt with the new ceramics and also with a new mechanical design which gave more mechanical freedom to one end of the capacitor. These rebuilt magnets now have about 7 10^7 shots on them without failures.

The use of commercial capacitors requires a tuning range for the inductance to create the correct characteristic impedance. This is accomplished by having the high voltage bus conductors mechanically adjustable. Measurements are made of the magnet parameters and then the bus conductors are moved to create the correct impedance.

C. CERN LHC Injection Kicker Magnet

The proton beams will be injected into the LHC at an energy of 450 GeV by two kicker magnet systems, producing magnetic field pulses of approximately 900 ns rise time and 7.8 μs flat top duration. To avoid dilution of the beam emittance during injection, a stringent design requirement of the system is a flat top ripple of the magnetic field of less than ±0.5%. Both injection systems are composed of 4 traveling wave kicker magnets of 2.7 m length each, powered by pulse forming networks (PFN's). To achieve the high required kick strength of 1.3 Tm, a comparably low characteristic impedance of 5 ohms has been chosen and ceramic plate capacitors with contoured rim have been used as matching capacitors for the magnet. Classical low inductance design with interleaving plates has been retained. Each of the 33 cells includes 2 ceramic plate capacitors with diameter 210 mm representing a capacitance of 4 nF. The capacitors are clamped in between the high voltage and ground plates and the contacts are ensured by spring contacts at the level of the rims. For stability reasons, capacitors made of class I ceramic have been selected. Three manufacturers have been qualified in Europe. Depending of the manufacturer, the permittivity varies between 75 and 90 and the temperature coefficient is 750 ppm/C.

The high-voltage behavior of such capacitors was unexpectedly poor under vacuum, with external breakdown problems, and the development work to achieve a reliable operation at 30 kV was very challenging. Successful results have finally been obtained by improving two important aspects that affect drastically the voltage holding:

a) The geometry of the transition between the connecting plates and the capacitor have been studied in detail and deflector parts have been implemented to eliminate the electrical field at the edges of the rim;
b) The vacuum quality has been improved mainly by means of a bake out at 300°C. The capacitors are only made of the monolithic ceramic part with the electrode surfaces made of silver layers. The standard glass passivation has been suppressed.

A ceramic tube with twenty-four 5 μm thick silver stripes onto the inner wall will be placed within the aperture of the magnet. The stripes provide a path for the image current of the beam. They are connected via decoupling capacitance to the standard vacuum chambers of the machine. A prototype magnet has been built. After bake out, the vacuum was level was as low as 3×10^{-11} mbar. The magnet has successfully been tested with 4×10^5 pulses at 30 kV.

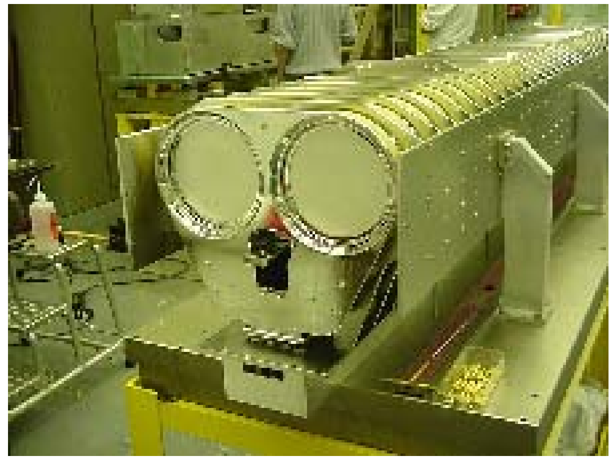

Figure 3. CERN LHC 5Ω prototype kicker magnet using ceramic capacitors, designed to accept 30kV pulses.

D. Other Development Efforts

As reported recently, KEK Photon Factory Storage Ring injection kicker magnet also adopted commercial ceramic capacitors to achieve a 6.25 ohm low impedance traveling wave magnet design. This 30-cell magnet uses silicon rubber molding to insulation and is placed outside of vacuum chamber. The operating voltage is limited to 15 kV due to difficulty of removing voids from silicon rubber molding.

IV. FUTURE NEED

The need of the traveling wave kickers with high permittivity and high permeability material is driven by the desire to have very high strength kickers within the available accelerator structure, to deflect particle beams of higher and higher energy.

Several fast kicker systems at Brookhaven's Collider-Accelerator Complex will be upgraded to inject/extract beams with higher energy and allow more operation flexibility, serviceability and maintainability. The BNL's AGS injection fast kicker upgrade will be a joint effort of BNL and TRIUMF. Presently, this kicker has three identical lumped inductance full ferrite magnets, with a field rise time of 95 ns and a fall time of 140 ns. It will be upgraded to inject 2.0 GeV beam from its current 1.5GeV level. The specification for this upgrade calls for even faster rise and fall time to allow more beam-bunches injected into AGS to achieve higher beam intensity. A traveling wave magnet design and development is necessary for this upgrade project. Its pulse lifetime is expected to be better than 5×10^8 for a minimum of 5 years of operation. To reduce the voltage stress of kicker magnets, we will add an additional straight section space for this upgrade. The Brookhaven's AGS extraction kicker future upgrade will be much more challenging, which will require a larger kicker aperture, single and multiple-bunch extraction, fast field rise and fall time, and very high radiation hardness. This kicker extracts a particle beam ranging from sub-GeV to 30 GeV and serves multiple programs with rapid switching. A traveling wave magnet kicker system would be a very attractive choice for this application. The radiation dose rate at this kicker location has reached to several tens of Rads/hour. Therefore, the material selection will be extremely important for this upgrade. A conceptual design of rapid cycling medical synchrotron for proton therapy has been conducted at Brookhaven National Laboratory. Its injection and extraction systems can be designed with a traveling wave magnet as well.

However, as summarized in section II and III, we notice that all traveling wave kicker magnets are operating under 40 kV at the magnet, with limited pulse lifetime in the order of 10^7 to 10^8 at best. This needs further development to achieve the multi-hundred-million pulse lifetime requirement for fast rep-rate accelerators. In addition to that, the fast rep-rate accelerators can have much higher radiation dose rate at kicker magnet regions, and heavier particles like proton and gold ions might cause more damage to the material than light particles such as electrons and positrons. Hence, development efforts must be addressed to the material level.

To achieve the goal of higher kicker strength with constrained kicker space, the use of very high permittivity capacitive components will be unavoidable. This indeed will push the fast kicker magnet design to the frontier of material research. The early endeavor of using high permittivity material in traveling wave magnet design was by R. Cassel of SLAC. A mock up magnet was built with alternate ferrite blocks and ceramic blocks. Its ceramic material, a composition of Magnesia, Calcia and Titania ($xMgO \cdot yCaO \cdot zTiO_2$), has a permittivity of 100 and higher. The design is very compact and carries the spirit of technical advancement. The following technical issues have to be well understood in the design of traveling wave magnet with very high permittivity materials.

1. The electric field gradient and stress release in the interface region of low and high permittivity materials;
2. The electric field gradient and stress release at region of conductor and high permittivity material interface;
3. The conductor and high permittivity material insertion/attachment technique;
4. The surface treatment of the high permittivity material;
5. The material permittivity versus temperature, moisture absorption, frequency, and voltage;
6. The material voltage hold-off versus temperature and moisture absorption;
7. The material voltage hold-off versus frequency;
8. The estimation of material voltage hold-off degradation rate versus integrated radiation dose;
9. The estimation of material voltage hold-off degradation rate versus particle types;
10. The estimation of material voltage hold-off degradation rate versus peak and average beam intensity.

In large accelerators, operation cost and user experiment costs easily over-run the design, development and construction cost of the kicker magnets. The performance and reliability of kicker magnet have direct impact to the accelerator's overall availability. A quantitative study of above mentioned issues will allow us to better estimate the technical limits of various designs, in terms of voltage hold-off, pulse lifetime, radiation damage rate, etc. Some of the studies outlined here are beyond the capability of the modern electrical test shop and machine shop. They have to be carried out with advanced scientific approaches used in material science research.

V. CONCLUSION

For traveling wave kicker magnet development, it remains to be a technical challenge to achieve higher voltage hold-off, longer pulse lifetime, high compactness, high reliability, etc. The technical challenges involved in this application can have significant impact to other pulsed power applications. For instance, many accelerator facilities have a very high radiation environment. The kicker magnets inside or surrounding beam pipes are subjected to very high level of radiation of different particles over many years, and radiation damage to the material is experienced everyday in the accelerators. The pulse lifetime requirement of kicker magnet can be as high as multi-billion pulses, a typical application of repetitive pulsed power system. The material interaction with various particle beams, directly or indirectly, can be a very interesting field of study. The large accelerator facilities have the very unique environment to examine many material and fabrication issues that is not available at universities and industries. However, the capability to analyze these issues tends to be the strength of university research. For many accelerator facilities, there is a limited requirement for kicker magnets although the need is very critical. Around the world, a small group of researchers sparsely distributed at various accelerator facilities have been working on this particular area of research. To link all the efforts together with university researches might benefit the accelerator society and the pulsed power society in a better way.

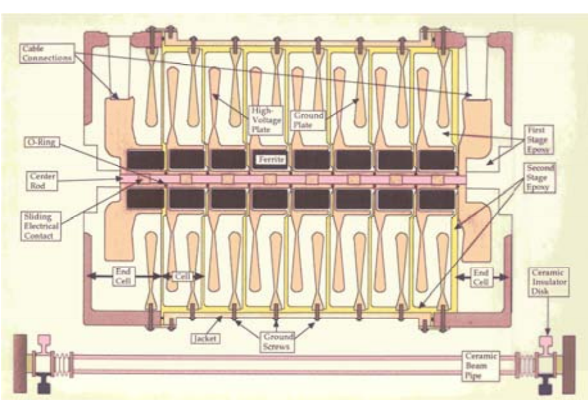

Figure 4. SLAC Epoxy Magnet

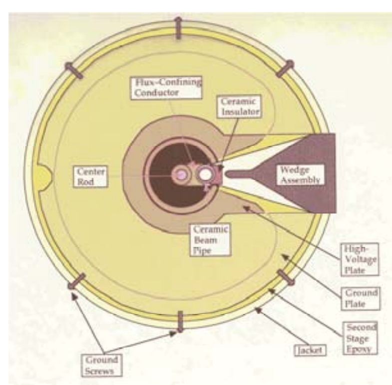

Figure 5. SLAC Epoxy Magnet End View