



**Fermi National Accelerator Laboratory**

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## **Injection Septum Magnets for the Loma Linda Medical Accelerator\***

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LOMA LINDA MEDICAL ACCELERATOR\***  
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Abstract

The injection beamline runs over the last magnet before a long straight section and is then displaced downward 55.88 cm to the accelerator beam-line. The displacement is magnetic and the final deflection onto the synchrotron orbit is by an electric kicker. The first component, the reverse septum magnet, bends the injection beam 25° downward. This is followed by the injection septum (20° bend upward) and the final injection kicker (5° bend upward).

The septum magnets produce a peak field of 3.4 K gauss at a current of 28,000 amperes within a 0.1 msec long pulse. The electric kicker produces a field of 7.3 KV/cm with a pulse length of 0.0011 msec. The septum magnets are similar to each other in construction with a bending radius of 72.7 cm. The curvature is required to increase the effective aperture. Each magnet has a single-turn copper coil bonded to a stainless steel plate for reinforcement. This eliminates insulating material, which could be subject to radiation damage, at the septum. The stainless steel plate is welded to the magnet laminations. The current is confined to the septum by the insulation between the laminations, which are a standard core material. The total septum thickness with shield is 1.27 cm. Pulsing the magnet eliminates the need for water cooling.

Introduction

Experience obtained from the operation of the pulsed septum magnets in the Fermilab Antiproton Source [1] was used to design the injection septum magnets described in this report. These septa will be used in the proton accelerator for the Loma Linda University Proton Therapy Facility.

These magnets are designed to produce a peak field of 3.4 K gauss with a bending radius of 72.7 cm. This will give an inflection system with injection energy of 3 MeV. Initially, a smaller aperture was used, but further beam studies showed that a good field aperture of 10 cm x 5 cm was required for the injected beam. Field calculations were made [2], and Fig. 1 shows the required septum cross section to obtain a field quality of  $\Delta B/B = \pm 0.05\%$  over the required aperture.

Injection septum magnets are usually critical components in accelerator systems. In this synchrotron, which is approximately 6 m in diameter, the beam injection location has very tight geometrical constraints. With the 10 cm magnet gap, a total septum thickness of 1.27 cm was necessary to operate within safe working stresses. This required production of a curved septum to avoid losing approximately 2.1 cm of aperture sagitta. Fig. 2 shows the injection beam geometry in the accelerator long straight section. In between the ring magnets, very little room is available for clearances between the various components. The injection septum and the electric kicker are both housed in a common vacuum chamber with final independent alignment adjustments for each one.

Pulsing the magnet eliminates the need for water-cooling the thin copper septum. However, the conductors undergo strong repelling cycling forces which lead to rupture caused by fatigue if not rigidly fixed. Explosion-clad metal consisting of 0.32 cm OFHC copper clad to 0.95 cm 304 stainless steel is used to enhance the mechanical strength.

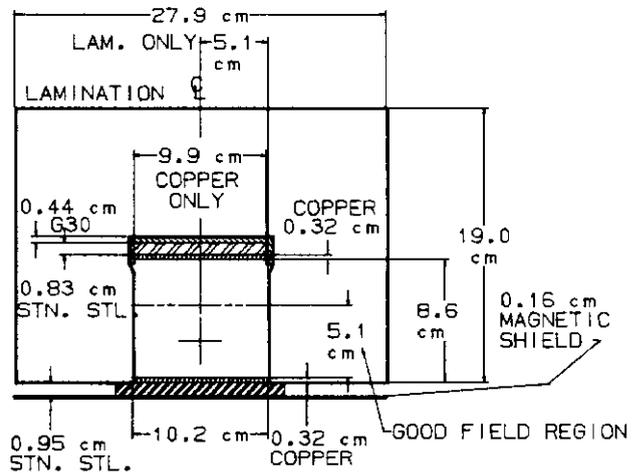


Fig. 1 Injection Septum Magnet Cross Section

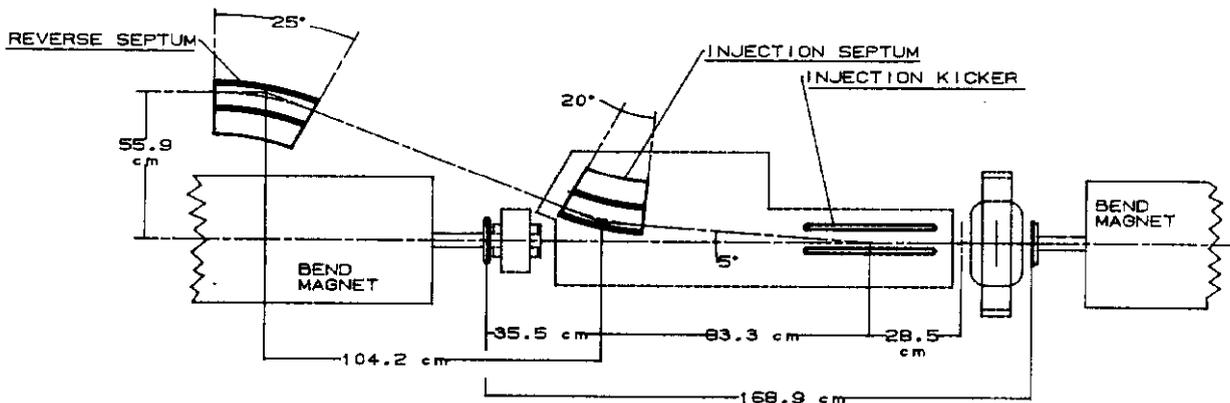


Fig. 2 Injection Beam Geometry

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### Magnet Design and Construction

The septum magnets are similar to each other in design. They both produce a peak field of 3.4 K gauss. The bending length of the reverse septum is 31.75 cm and 25.4 cm for the 20° bend injection septum. The cross section of the injection septum magnet is shown in Fig. 1. The total septum thickness is made up of three components: 1) a copper bus carrying a pulsed current of 28,000 amp, 2) a stainless steel plate metallurgically bonded by explosive cladding to the copper, 3) a low-carbon steel plate to shield the circulating beam magnetically. The inner conductor is also bonded to a stainless steel reinforced plate. This composite laminate is electrically insulated to the lamination with a 0.4 cm thick G-30 channel. The cross section of the injection septum and the electric kicker enclosed in a common vacuum box are shown in Fig. 3. The rough alignment is made from the enclosure supports. Each component has independent fine adjustment made inside the box through the flange openings. The electric kicker has a fixed bottom electrode which is the cathode. The top electrode is adjustable using metal shims to accommodate the injected beam size. The injection septum is closer to the circulating beam. The magnet is supported at three places using alumina ceramic balls. An isometric sketch (Fig. 4) shows the magnet support. Vertical rotation and twist adjustments, about the fixed ball, can be made by inserting or removing metal shims under the bolt connections. The septum will need fine adjustments to fit between the circulating beam and the injected beam for minimum beam losses. At the crossover connection near the circulating beam, the coil is extended, keeping the copper surface constant between the septum and the inner conductor to minimize end-field effects. The crossover conductors are also bonded to stainless steel support plates. At the septum, the stainless steel plate is welded to the core giving a good rigid construction.

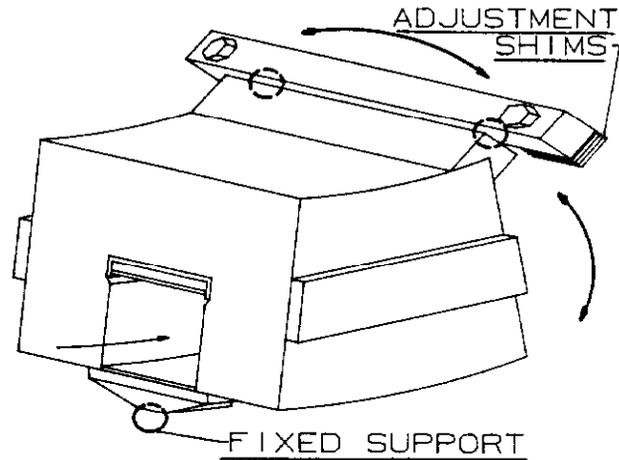


Fig. 4 Injection Septum Magnet Support and Adjustment System

Since the laminations are insulated from each other by the core material, the current is constrained to flow along the septum, mostly on the skin of the copper inner surface. The low-carbon steel plate extend past the connection to minimize the fringe field outside the septum at the end. The power connections to the magnet are symmetrical to the gap center line and are clamped to the core with a ceramic block. The composite laminate is used all the way to the power feedthrus. The inner conductor is insulated from the core, and the magnet assembly is constrained within the three alumina ceramic balls; therefore, the magnet is electrically insulated to the vacuum box.

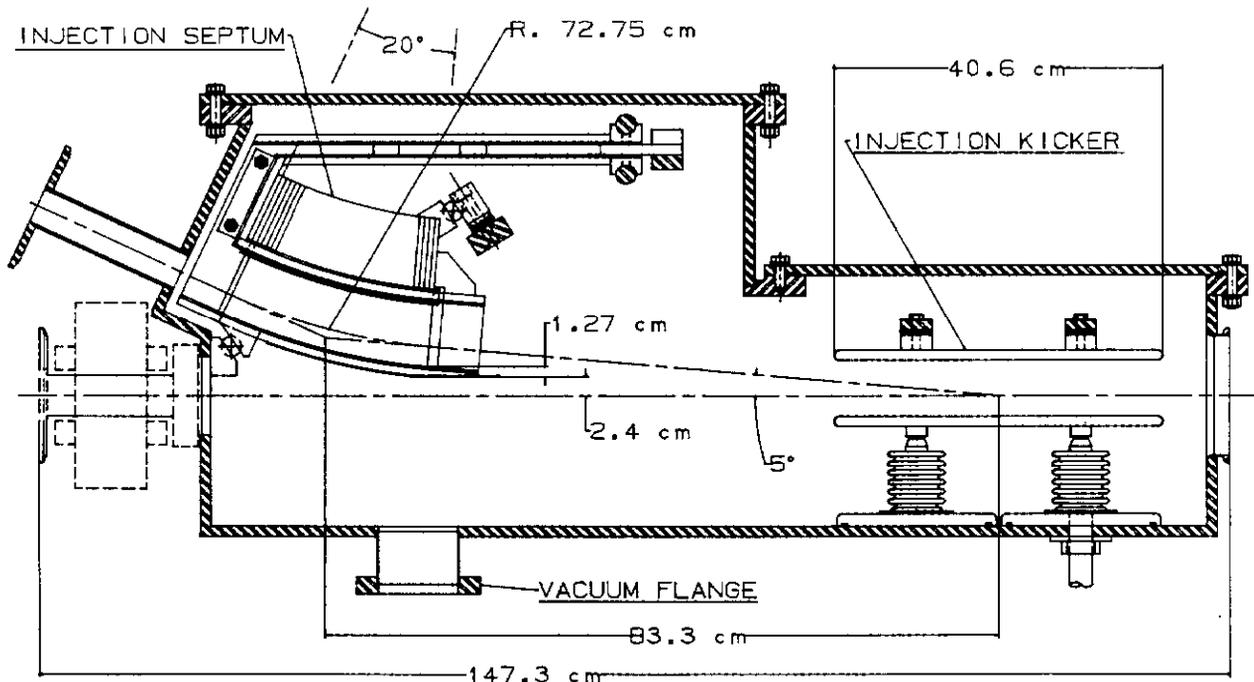


Fig. 3 Injection Septum and Kicker Assembly

The power leads are clamped with ceramic insulator spacers to constraint the repelling forces from the high current. The cantilever design of the lead assembly will allow small magnet adjustments with limited forces exerted to the power feedthrus.

An average vacuum of  $10^{-7}$  torr is required. The vacuum box is made from 316L stainless steel which has been vacuum degassed. The only organic material that will be exposed to the vacuum will be the G-30 insulation in the magnet and O-ring in the flanges. The laminations used in the magnet core will also be vacuum degassed at high temperature before stacking. Before final installation the core assembly will be baked in a vacuum. Outgassing from the magnet assembly is estimated at about  $1.5 \times 10^{-5}$  torr-liter/ $\text{cm}^2$  sec. An additional pump of 140 l/sec is installed at the injection vacuum enclosure.

#### Lamination and Core

The magnet laminations were punched from a 0.35 mm electrical steel type M-22. The required tolerances in the gap are  $\pm 0.03$  mm. The surface is coated with a phosphate insulation, resistance AISI C-4. Because the magnet is in a  $10^{-7}$  torr vacuum, the laminations are vacuum baked at  $780^\circ\text{C}$  and degassed for two hours. This baking process removes residual gasses trapped in the metal during fabrication.

The core is assembled by stacking laminations on a curved fixture. Under compression, steel plates are welded on the side of the laminations to hold the core together. The core is then machined to a pie shape. The face of the core is machined to the required curvature for welding the septum composite assembly. Before final coil assembly, the core is baked to remove any contamination obtained during machining.

#### Coil and Assembly

The magnet is designed to be pulsed once every two seconds. A rectangular pulse with a characteristic frequency of 5000 Hz will be used to drive the current through the magnet. Taking into account the skin effect, an average power of only 5.8 watts is dissipated in the coil. Cooling is provided by conduction mostly through the copper feedthru rods. Some heat will be conducted through the ceramic ball supports to the skin of the vacuum chamber. The power connection bus terminals will be water cooled. Assuming all the heat to be conducted through the copper bus, a temperature gradient of  $12^\circ\text{C}$  was calculated for the coil's extreme points.

In the 3.4 K gauss field region, the cycling force on the conductor is 96300 Pa. It is this repetitive force that can cause fatigue rupture in the copper conductor and voltage breakthrough from abrasive damage to the insulation. Stainless steel backing bonded to the copper and rigid clamping are the solutions to the cycling force problem. The copper conductor is metallurgically and uniformly bonded to the stainless steel support plate by the explosive-cladding process. This was found to be the best method of obtaining uniform bonding of the two metals. The clad material is purchased in plates to the desired metal thickness. Parts for the coil are

cut, bent, and machined to shapes. At the corners, TIG welds are used to weld the metals. Full penetration fillet welds are used for the copper.

The G-30 insulation channel is first inserted in the core and epoxied in place. Final machining for a snug fit with the inner conductor is then made. The inner conductor, machined, and with the ends already welded on, is then installed and epoxied inside the insulating channel. The copper surface of the inner conductor is then machined to a tighter tolerance of  $\pm 0.05$  mm in the bending radius and  $\pm 0.04$  mm to the core gap. These dimensions are critical for obtaining the good-field aperture quality. The septum conductor is finally clamped to the machined face of the core and welded. Maximum accumulating tolerances of  $\pm 0.1$  mm are required. These tolerances were achieved with existing operational septum magnets.

#### Injection Septum Magnet Parameters

Maximum Field (for 3 MeV)	3.4 K gauss
Bending Radius	72.7 cm
Bending Angle	$20^\circ$
Magnet Length	25.4 cm
Aperture Width	10 cm
Aperture Height	8.25 cm

#### Septum Thickness at Injection

Copper	0.32 cm
Stainless Steel Backing	0.79 cm
Magnetic Shield	0.16 cm
Total Thickness	1.27 cm

Pulsed Current	28,000 A
Rectangular Pulse	
Characteristic Frequency	5000 Hz
Pulse Interval	2 sec.
Pulse Duration	$< 100 \mu\text{sec.}$
Coil Average Power	5.8 W
Pressure on Conductor	96,300 Pa

#### Summary

Pulsing septum magnets eliminate the need for water cooling. The fatigue problems from the cycling magnetic forces can now be overcome by using clad materials to reduce fatigue stresses in the conductors. Rigid fastening is important to minimize insulator material wear.

#### Acknowledgement

I wish to thank D. Schmitt for drawing the detail design.

#### References

- [1] J.A. Satti and S.D. Holmes, "A pulsed Septum magnet for the Fermilab Antiproton Source," IEEE Trans. Nucl. Sci., Vol. NS32, pp 3628, Oct. 1985.
- [2] S.C. Snowdon, "Injection Septum Field Calculations", Fermilab LL256 Report.