# Fabrication Techniques for Septum Magnets at the APS

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**Abstract**

The design, construction, and installation of pulsed septum magnets for particle accelerators presents many challenges for the magnet engineer. Issues associated with magnet core structure design, component alignment, weldment design, and electrical insulation choices are among those requiring careful attention. The designs of the six septum magnets required for the APS facility have evolved since operation began in 1996. Improvements in the designs have provided better injection/extraction performance parameters and extended the machine reliability to meet the requirements of a world-class, third-generation synchrotron radiation facility. Details of the techniques used to address issues involved in producing septum magnets at the APS are described here to aid magnet engineers in the fabrication of future septum magnets.

**Keywords:** septum, magnet

## 1. A Review of Septum Magnets at the APS

A description of the original septum magnets used at the APS can be found in a paper by Gorski et al. [1]. Since then the synchrotron injection septum was changed from an eddy-current-shielded in-vacuum magnet to a direct-drive out-of-vacuum magnet [2], and the electrical connections in the storage ring thick septum were changed. The storage ring thick septum was flipped end to end to place the electrical flags further from the stored beam to reduce interference from the stray magnetic fields induced by the electrical connections. Currently a new synchrotron extraction direct-drive septum with the core out of vacuum is being built to replace the existing, in-vacuum eddy-current-shielded magnet. Also a new storage ring injection septum, being built at the APS to replace the existing one, will have a new downstream transition and an improved weld at the downstream end of the septum gap. This weld will be discussed later in this paper.

## 2. Cores

All septum cores at the APS are made of M22 silicon steel laminations with a C5 coating on both sides. The M22 silicon steel provides good magnetic field properties for pulsed magnets while the C5 coating provides electrical insulation between the laminations. The lamination thickness is 0.18 mm for the synchrotron injection septum and 0.36 mm for all of the other septa. The 0.18-mm-thick lamination was chosen to reduce eddy current effects within the core.

### *2.1 Core End Packs*

Each septum core has an end pack at each end that contains the required shaping of the core edges to properly terminate the magnetic field and reduce electric field gradients near the coil. Core end packs are preassembled prior to core stacking to facilitate the special shaping at the core ends. Core end packs, with the exception of those in the Positron Accumulator Ring (PAR) septum, are made of laminations bonded together with epoxy. Figure 1 shows the end pack used for the storage ring injection septum and the synchrotron extraction septum. The radius shown is needed because this corner gets very close to the septum conductor. This radius reduces the possibility of electrical arcing between the core and the conductor. The end pack is machined with an approximated Rogowski surface in order to minimize eddy currents that can cause thermal heating and undesirable leakage fields.

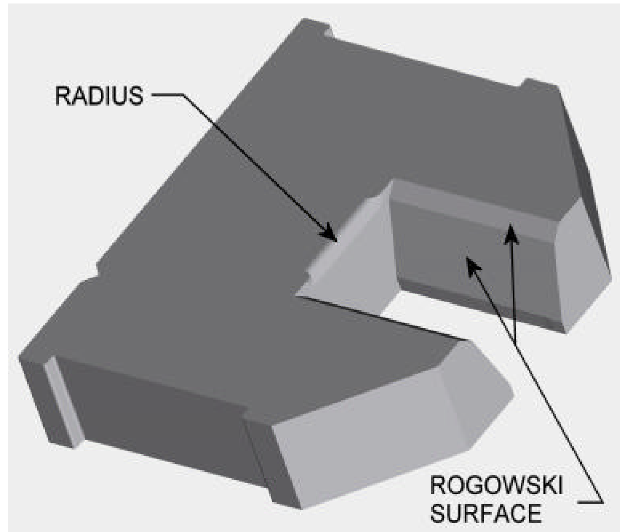


Fig. 1: Storage ring injection septum and synchrotron extraction septum end pack.

Core end packs are made by stacking laminations coated with heat cure epoxy in a stacking fixture that keeps the assembly aligned. The lamination stack is compressed to 700 kN/m$^2$ (100 psi) in the stacking fixture while the epoxy is heat cured. The end pack is removed from the stacking fixture and the Rogowski surface and radius are machined. Care must be taken to avoid delamination while machining the Rogowski surface. The machinist clamps the end pack firmly between two 6.5-mm-thick aluminum plates. The aluminum plates are cut along with the end pack and discarded after machining. A right-hand cutting tool is used to cut the Rogowski surface on one side in a direction such that the cutting edge pushes the laminations together to prevent delamination. A left-hand cutting tool is used to cut the Rogowski surface on the facing side in the same manner.

The PAR septum end pack, shown in Figure 2, is made of a combination of GLID-COP Al-15 and laminations. The PAR septum core is pulsed in a vacuum at 60 Hz. All other septa at the APS are pulsed in air at 2 Hz. This makes the PAR septum more susceptible to overheating. Several tests were performed on many different styles of end packs and overheating could not be reduced to acceptable levels even when using an approximated Rogowski surface. Water cooling was necessary to remove the heat for this septum. Since this end pack is inside a vacuum, the laminations cannot be bonded together

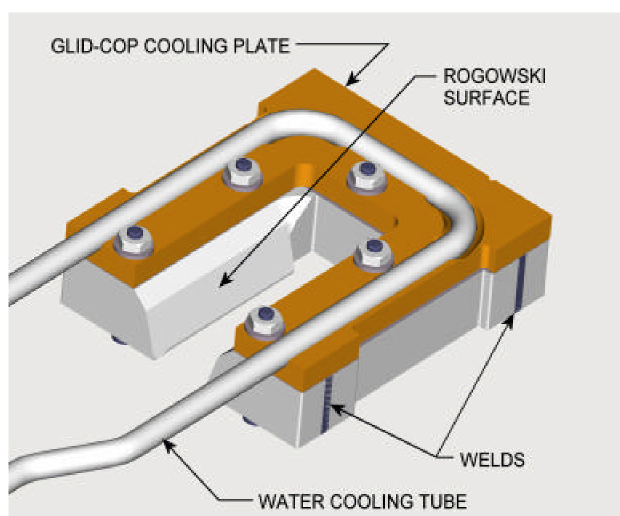


Figure 2: PAR septum end pack.

with epoxy. Instead the lamination stack is welded together prior to machining the Rogowski surfaces. The cooling tube is furnace brazed to the GLID-COP Al-15 plate, and the assembly is bolted together as shown in Figure 2. All these tasks must be performed in an ultra-high vacuum clean environment for $10^{-9}$ Torr operation.

### *2.2 Rogowski Surface*

At the ends of a pulsed septum core the field lines tend to leave the core perpendicular to the surface of the laminations. This creates eddy currents in the laminations that can cause excessive heating and undesirable stray fields, and create forces perpendicular to the plane of the laminations that promote delamination. The core ends can be shaped to reduce these eddy currents; one possible shape is a Rogowski surface [3]. The equation for an ideal Rogowski surface is:

$$y = y_0 + \frac{e^{kx}}{k}, \tag{1}$$

where y is the distance from the midplane to the pole face, $y_0$ is the half gap height, $k=p/(2y_0)$, and x is the transverse distance. A double chamfer approximating a Rogowski surface is used at the APS and reduces eddy currents at the ends of the cores. This double-chamfered surface is shown in Figures 1, 2, and 3.

### *2.3 Septum Core Welding*

The laminations along with the end packs of a storage ring thin injection septum core are held together with 316 stainless steel tie bars that are stitch welded in place. One of the problems we encountered after welding the core was the laminations on the ends becoming susceptible to delamination because heat and distortion from the welding compromised the epoxy bond of the last few laminations on the end pack. The only things holding the last lamination on are six 5-mm fillet welds attached to a thin lamination. These welds could easily break and the last lamination would fall off, exposing the next lamination to similar effects.

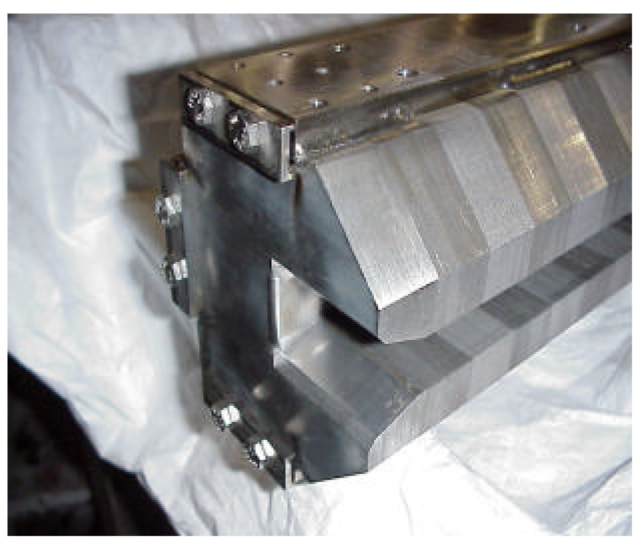

Fig. 3: Septum core end with clips.

This problem is solved by installing clips, shown in Figure 3, to hold the last lamination in place during welding. First the core laminations and the preassembled and machined end packs are stacked in a fixture that keeps the gap straight and precisely controlled. Tie bars are clamped in place and the laminations are compressed to 3,400 kN/m$^2$ (500 psi). The tie bars are welded to the core with 5-mm fillet, 50-mm long staggered stitch