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.

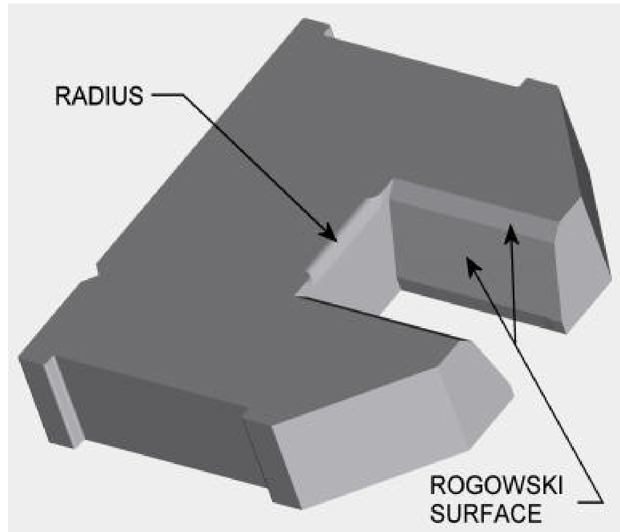

Fig. 1: Storage ring injection septum and synchrotron extraction septum end pack.

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

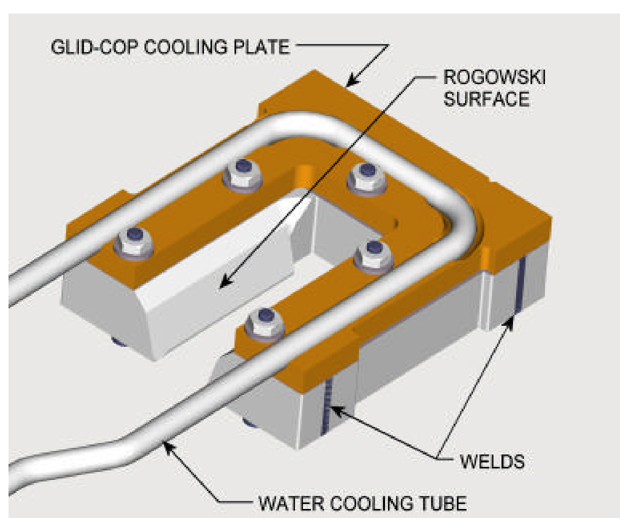

Figure 2: PAR septum end pack.

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.

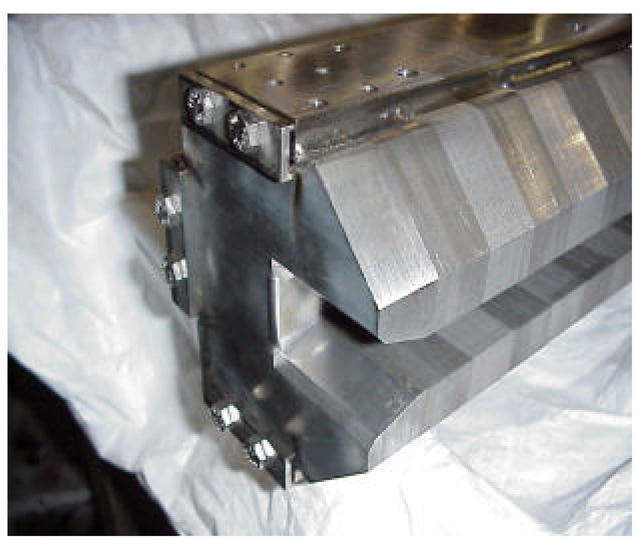

Fig. 3: Septum core end with clips.

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 welds all the way up to but not including the end packs. The partially welded core is removed from the stacking fixture to allow room for the clips to be attached. The welding of the tie bars is finished with the clips in place. The epoxy bonds of the end laminations are subsequently fully intact. The core can be used with or without the clips.

3. Conductor Assembly

Septum conductor assemblies are made of sections of OFHC copper welded together. Kapton tape, Nema grade G-10, and ceramic are used to electrically insulate the conductor assembly from the laminated core, field-free tube, transport tube, and other parts of the magnet. The original septum magnets built at the APS had conductor sections assembled in the core along with the insulation material and transport tube. Then the core was impregnated with moldable ceramic to lock all pieces in place. The conductor assembly was then welded together in the core. Unfortunately, heat from the welding spread to sections near the Kapton tape and Nema grade G-10, compromising the effectiveness of the insulation properties of the Kapton tape and damaging the Nema grade G-10 in spots. This damaged insulation could not be replaced because everything was locked in place with the moldable ceramic.

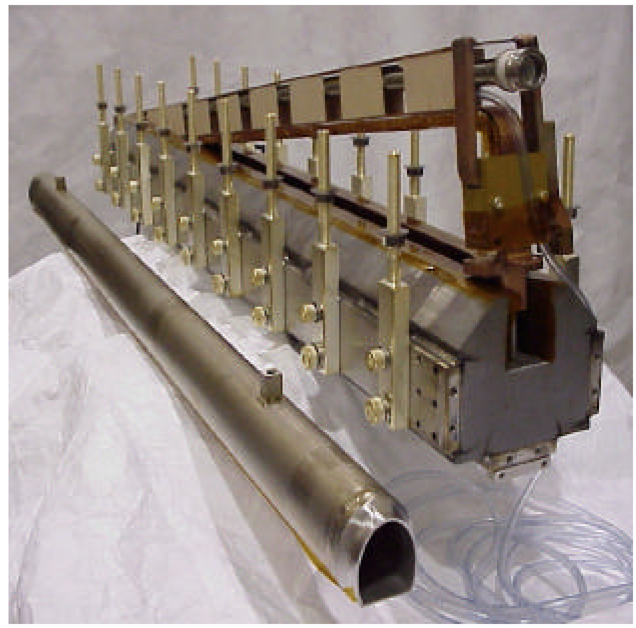

Figure 4: Synchrotron extraction septum conductor assembly partially installed in the laminated core.

Designing the conductor assembly to be completely welded outside the core eliminated this issue. No Nema grade G-10 was present during welding. Cooling packs were used to reduce heat transfer to sections containing Kapton tape. If the Kapton tape did get burned it could be replaced before the conductor assembly was installed in the core. Figure 4 shows a fully welded conductor assembly partially installed in the core for the synchrotron extraction septum. Welding this way also made it easier for the welder to access the welds located in tight places.

4. Beam Tubes

Septum magnets require a field-free tube, made of low carbon steel, to reduce the effects of the leakage field on the stored beam. Septum magnets made with the core outside of the vacuum require a transport tube inside the magnet gap to enclose the ultra-high vacuum region. The field-free tube and transport tube come very close together at one end of the magnet and are joined to a flange with vacuum-tight welds. These welds are very close together and can result in unacceptable weld build-ups and vacuum leaks if not managed correctly. These are manual welds using the gas tungsten arc weld process.

Figure 5 is a drawing of the original storage ring thin septum beam tube welds. The field-free tube (1026 DOM) has a 316L SS transition piece welded to each end. The end of the field-free tube (316L SS) is welded to the flange (304 SS). Due to the metallurgical considerations in the weld metal, the degree of constraint, and the close proximity of the welds in the field-free tube, transport tube, and flange, there is a high propensity for weld metal cracking. When the transport tube (625 Inconel) is welded to the flange, the heat from welding would crack the weld between the field-free tube and the flange. The welder would repair the crack using Inconel filler, but heat from the weld repair would crack the other weld. This cracking would continue until enough Inconel filler metal was applied to avoid any further cracking. However, at this point the required septum thickness could not be maintained.

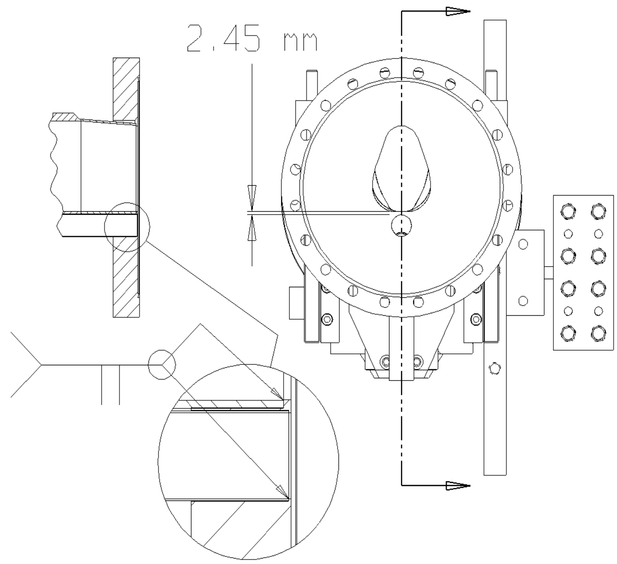

Figure 5: Original method for welding the storage ring thin injection septum tubes.

Figure 6 shows a finished vacuum-tight weldment using the old method for the storage ring thin injection septum. The target dimension for the total septum thickness is 2.45 mm. This has not been achieved because the additional weld filler required to repair the weld cracks increased the thickness to 3.5-4.5 mm. Any attempt to grind the weld down to 2.45 mm usually caused a crack that needed to be repaired again.

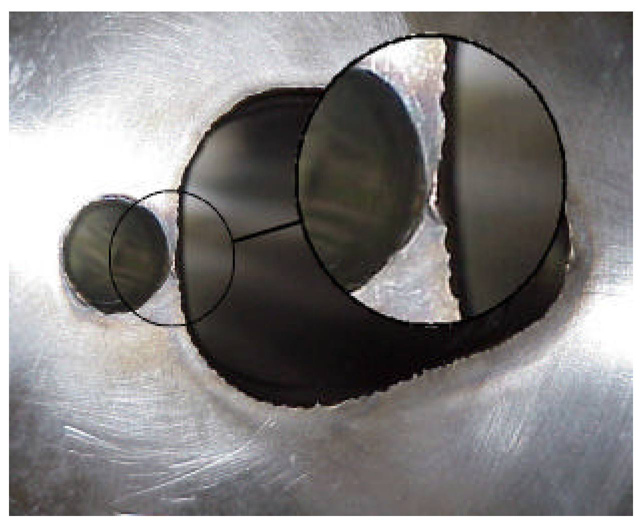

Figure 6: Storage ring thin septum tubes welded using the old method.

A much-improved welding method has been successfully used for the synchrotron extraction septum. This concept is shown in Figure 7. The flange is made of 304L stainless steel. A counter-bore is machined into the flange where the 625 Inconel transport tube (0.35-mm wall thickness) is welded. The field-free tube, pictured in Figure 4, is made of low-carbon steel in the center and transitions to 304L stainless steel about 20 mm from each end. This allows a 304L-to-304L fusion weld joint for the field-free tube to the flange joint (J2). The field-free tube is welded to the flange first without the transport tube installed. This sequence is critical because heat from the field-free tube-to-flange weld can penetrate through the wall and crack the transport tube

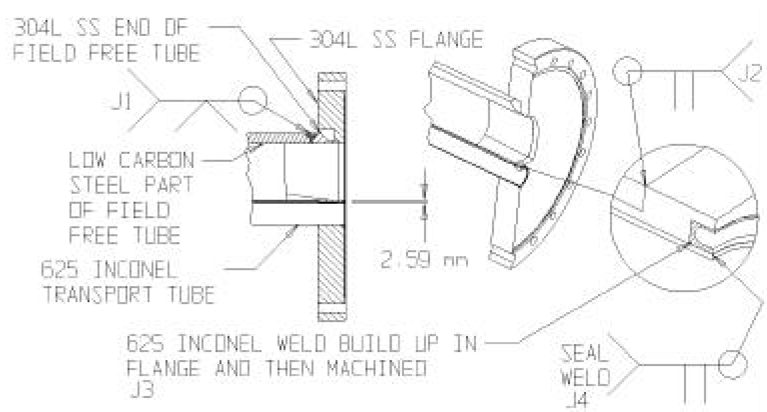

Figure 7: Cutaway views of the synchrotron extraction septum tube welds.

if it is in place. Before welding the field-free tube to the flange, a removable copper plug is tightly inserted into the hole, where the transport tube fits, to act as a heat sink and to minimize any warping of the small hole. After the flange is welded to the field-free tube (J2) the copper plug is removed and the counter-bore in the flange is filled with two layers of 625 Inconel filler metal. The weld overlay on the flange is then machined with a 0.35-mm-thick weld prep at the transport tube joint. This allows for an Inconel-to-Inconel fusion weld edge joint with similar thicknesses at the transport tube-to-flange weld joint. The transport tube can now be easily inserted and welded. It should be noted here that no weld filler is added for either the field-free tube-to-flange joint (J2) or the transport tube-to-overlay joint (J4).

The storage ring injection septum is currently being modified to give it a shorter septum gap length, a smoother transition between the two apertures of the septum magnet assembly, and a single large aperture of the storage ring vacuum chamber in order to minimize wake field losses and improve the weld near the end of the septum gap. This new design is shown in Figure 8. The cap transition is welded to the field-free tube before the transport tube is installed, otherwise heat from the welding could penetrate through to the transport tube and crack it. A bevel weld is used at J5 because this weld joins two dissimilar metals requiring an Inconel filler material. As in the synchrotron extraction septum tube welds, a removable copper plug is tightly inserted into the hole, where the transport tube fits, to act as a heat sink and to minimize any warping of the small hole. After welding the cap transition to the field-free tube, the plug is removed and the transport tube is inserted and welded to the cap transition. Next, the downstream transition is welded to the

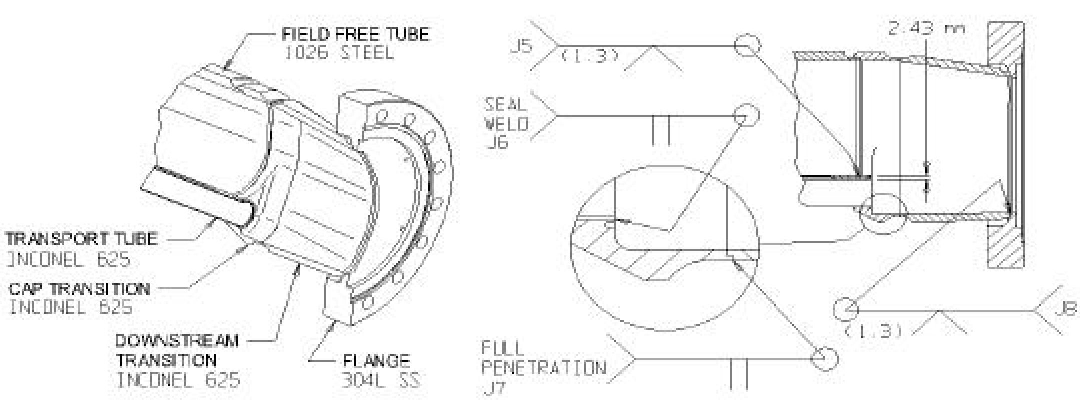

Fig. 8: Cutaway views of the new modified storage ring injection septum.

cap transition. This is an Inconel-to-Inconel fusion weld. This weld must have full penetration to avoid virtual leaks in the ultrahigh vacuum, so the wall was made thin (1.6 mm) and constant all the way around the weld joint. The flange is welded to the downstream transition with a bevel weld joint because this is an Inconel-to-304L stainless steel weld and is easier to weld vacuum tight when a filler material is used.

5. Alignment

In order to ensure that a septum magnet installation or replacement goes smoothly, a well-defined procedure must be followed. This procedure should address safety hazards, safety practices, personal protective equipment, a preparation check list, a check list to remove the existing magnet, a check list to install the replacement magnet, a survey and alignment procedure, a bake-out procedure, and a post-installation inspection. This section focuses on the survey and alignment part of the installation procedure.

The alignment procedure starts with the fiducialization of the septum magnet. In this step the relation between the stored beamline and external reference markers is established using the septum surface as a physical reference. The coordinate system in which to establish the fiducial marks is a right-handed beam-following system with the origin at the geometric center of the magnet on the stored beam centerline (Figure 9). The positive z axis is defined along the stored beamline in the beam direction. The y axis is parallel to the gravity vector at the origin, and the x axis is perpendicular to both the z and y axes. During the fiducialization step the physical septum, offset by 18 mm from the stored beam, is referenced while the magnet is level averaging readings across the top of the core near the supports. At that time it is advisable to request the measurement of the flange centers in the same coordinate system for later reference by the physics or mechanical engineering groups.

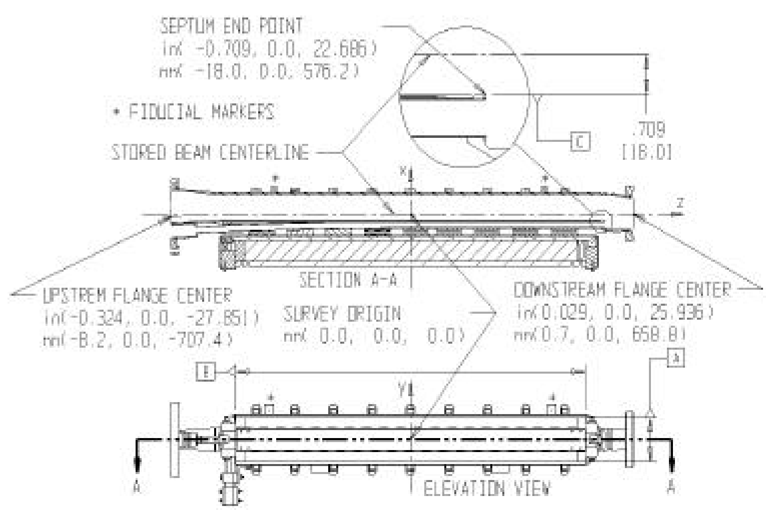

Fig. 9: Storage ring thin septum alignment drawing.

Step two requires the positioning of the septum magnet in the storage ring at the APS global coordinates x=166.5880, z=55.3672 m. The orientation of the septum is given by the location of the quadrupole centers on either side of the septum as defined by the APS lattice. This ensures that the stored beam centerline in the magnet coincides with the actual stored beam.

6. Conclusion

We have presented just a few of the methods used to address the challenges that the septum magnet engineer has to tackle. These practices have been used at the APS, but other accelerator facilities may successfully build their septum magnets using some different methods. This paper is intended to provide suggestions for designing and building septa.

7. Acknowledgements

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8. References

[1] A. Gorski, R. Wright, C. Pitts, S. Sharma, “Design and Construction of Septum Magnets at the 7-GeV APS,” Proc. 1999 Particle Accelerator Conference, pp. 3342-3344 (1999).

[2] M. Jaski, K. Thompson, C. Doose, J. Humbert, R. Wright, “New Booster Injection Septum Magnet at the APS,” Proc. 2001 Particle Accelerator Conference, pp. 3230-3232 (2001).

[3] K. Halbach, Lecture notes from APS seminar “Fundamental Properties of Magnetic Fields,” July 1992.