BTS1 Septum Magnets

CLS DESIGN NOTE - 4.2.31.1 Rev. 0

(formerly 2.1.41)

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1. Introduction

The Booster to Storage ring (BTS1) septum magnets are the last two elements of the transfer line which transports the beam from the booster to the storage ring. The first of these magnets is a so-called “thick” septum, i.e., the geometry of the transfer line allows the septum thickness to be up to ten centimeters. The thick septum is followed by a “thin” septum which is the element that delivers the beam to the injection point of the storage ring. As described in the injection design note[1] , the thickness of the thin septum should not be greater than 3.0 mm.

The total bend supplied by the two septa must be 16.0 degrees. The thin septum is chosen to have the same design parameters as the booster extraction septum, including a 7.62 degree deflection angle. The thick septum has a bend angle of 8.38 degrees.

The layout of the two BTS1 septa is shown in Figure 1.1. This figure also shows elements of the storage ring injection straight: the two quadrupoles (Q1) at the ends of the straight and the two injection kickers surrounding the injection point. The injection point is defined to be at the downstream end of the thin septum. At this point the injected beam is 26.0 mm from and parallel to the storage ring axis. (see also Figure 3.1)

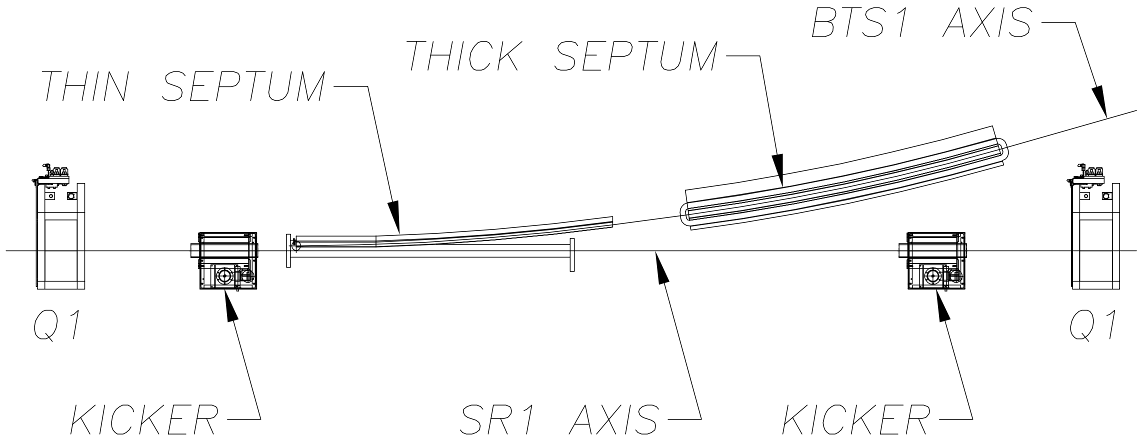

Figure 1.1. Layout of BTS1 septa.

2. Thick Septum Magnet

The magnet plan view is shown in Figure 2.1 and the cross-section is shown in Figure 2.2. The thick septum magnet is required to bend the beam 8.38 degrees. A magnet arc length of 1.655 m is proposed. A "C"-shaped magnet with a full gap of 20 mm is proposed. With this gap a good field region of ±15 mm can be produced with a pole width of 60 mm. Small bumps at the edge of the poles reduce the gap to 19.7 mm. To keep the pole width small, a curved magnet is considered. Outside the exterior coil the field is clamped with 20 mm of iron. The distance from the center of the pole to the outside of the field clamp is 83 mm.

The magnetic properties of the thick septum magnet have been studied with POISSON. For this analysis, AISI 1010 steel was used. (The B-H curve for the steel is given in Appendix III.) The POISSON (Automesh) input file is given in Appendix I.

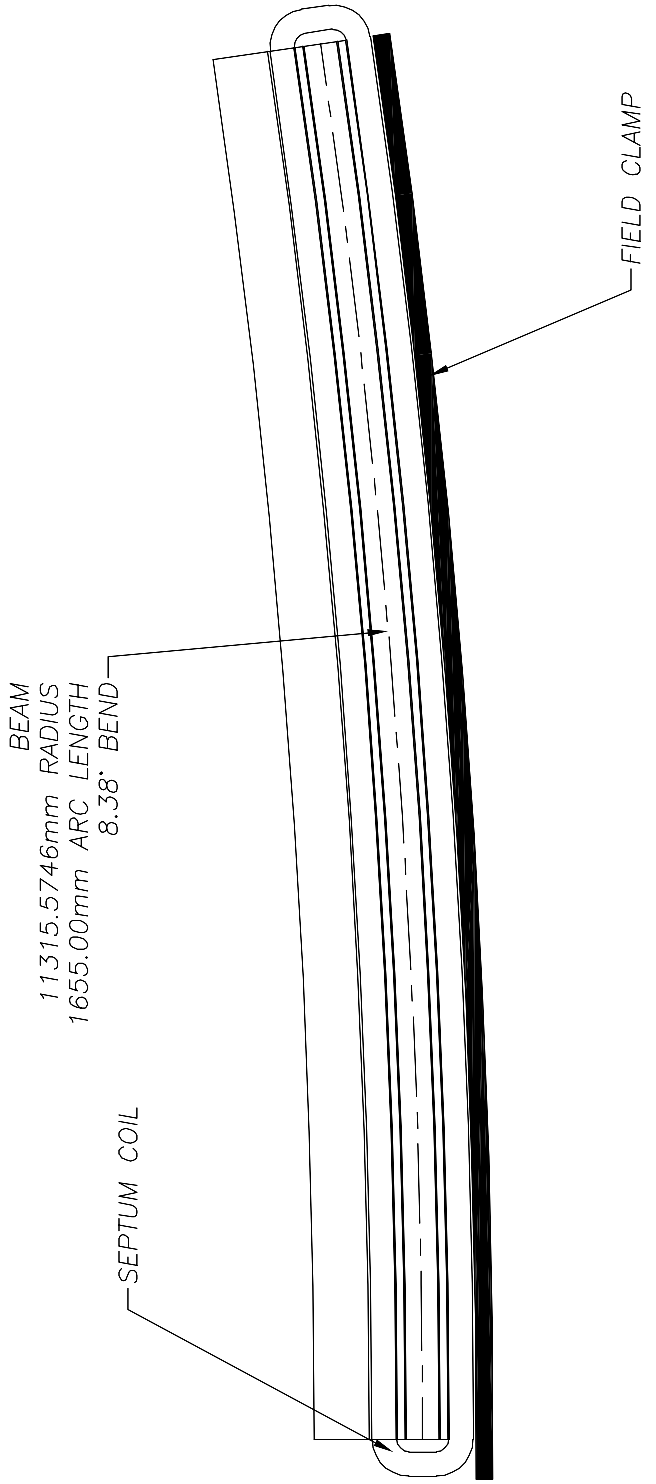

Figure 2.1. Plan View of the Thick Septum Magnet

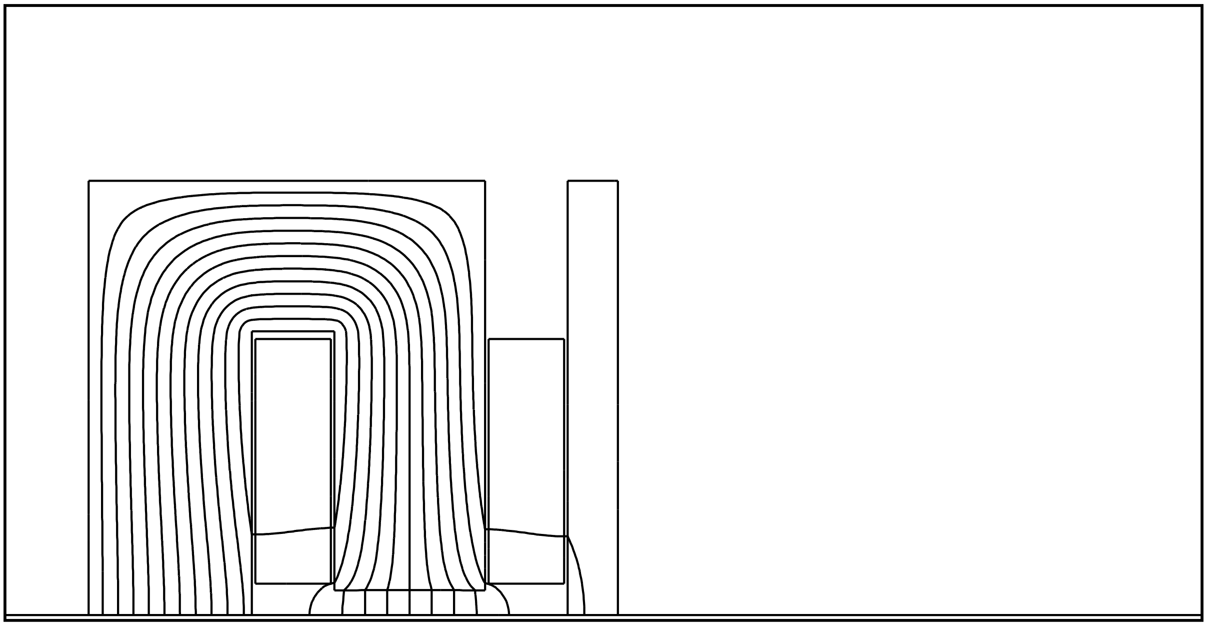

Figure 2.2. Cross-section of the Thick Septum Magnet

The magnet excitations are given in Table 2.1. Fields are given at the center of the pole where the beam will reside. The nominal field to bend a 2.9 GeV beam is 0.85427 T. In the table, the beam energy, E, corresponding to the given dipole field is given. Also given is the calculated efficiency and the maximum stray field just outside the field clamp. This stray field diminishes sufficiently at the position of the stored beam in the storage ring.

Table 2.1. Thick Septum Magnet Excitation.

N-I	B	B’	B’’	B’’’	E	Efficiency	B_{stray}
Ampere-turns	T	T/m	T/m^2	T/m^3	GeV	%	T
4000	0.49497	-3.67E-4	-7.08E-2	5.41E0	1.680	98.5	1.3E-4
7200	0.87317	-3.84E-4	-3.52E-1	1.08E1	2.964	96.5	1.9E-4
8000	0.94741	-3.97E-4	-5.19E-1	1.30E1	3.216	94.2	2.0E-4

The good field region of thick septum magnet is shown in Figure 2.3. The plot shows the deviation, $\Delta B = B(x) - B(0)$, of the field of the magnet relative to the central field, B(0), as a function of position X from the centre.

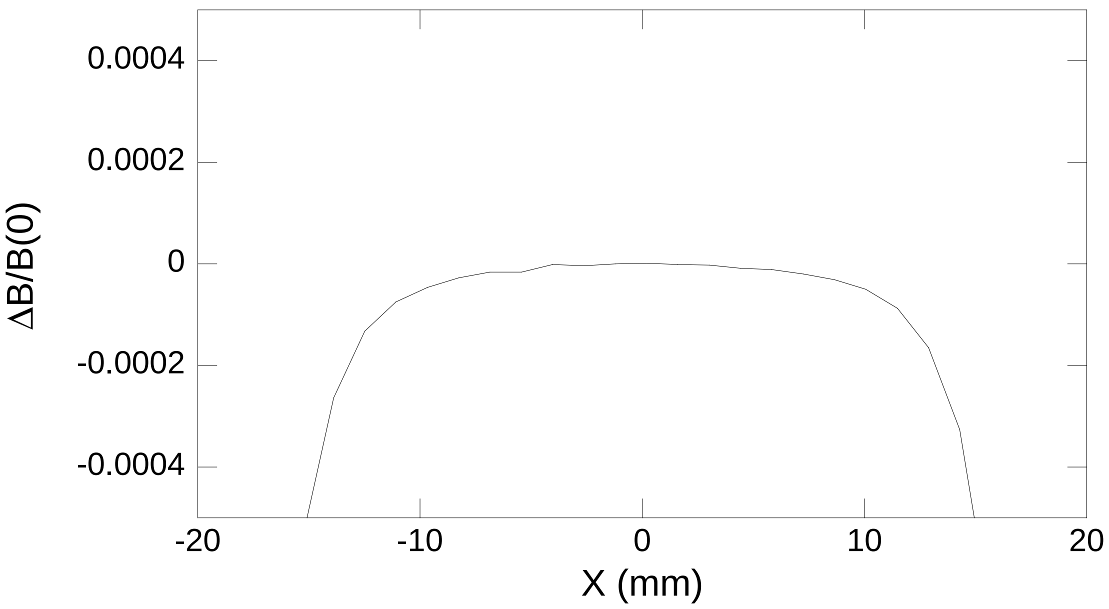

Figure 2.3. Thick Septum Magnet Good Field Region

The basic magnet design parameters are given in Table 2.2. The coil is assumed to have 90 windings of 4.76 mm square conductor with a 3.18 mm diameter cooling channel. To achieve the maximum ampere-turns of 8000, then, 89 amperes are required.

Table 2.2. Thick Septum Magnet Parameters.

Bend angle	8.38	degrees
Field strength @ 2.9 GeV	0.8543	T
Field strength (maximum)	0.9474	T
Magnet arc length	1.655	m
Radius of curvature	11.316	m
Magnet gap	20	mm
Good field width	30	mm
Number of coils	2	
Ampere-turns (maximum) per coil	8000	
Number of windings per coil	90	
Current (DC)	89	A
Conductor area (less cooling channel)	14.72	mm^2
Conductor length per coil	320.5	m
Total conductor length	641.0	m
Resistance (copper)*	0.75	Ω
Voltage drop	66.8	V
Power	5.95	kW

*resistivity = 1.72 E-8 Ω m

3. Thin Septum Magnet

The thin septum magnet is required to bend the beam 7.62 degrees. A magnet arc length of 1.655 m is proposed. A “C”-shaped magnet with a full gap of 15 mm is proposed. The magnet plan view is shown in Figure 3.1. This figure indicates the position of six cross-sections that are shown in Figures 3.2 through 3.6. As shown in the figures, the excitation coils are inside the magnet gap. The thin coil is 1 mm thick while the other coil is 5 mm thick. To keep the pole width small a curved magnet is considered. Between positions 1 and 2, however, the magnet is straight. Over this straight section the BTS1 beam axis goes from 12.5 mm from the (inside of the) thin coil to 5.5 mm from the thin coil.

The magnetic properties of the thick septum magnet have been studied with POISSON. For this analysis, AISI 1010 steel was used. The POISSON (Automesh) input file is given in Appendix II. At 2.9 GeV the desired field is 0.77680 T.

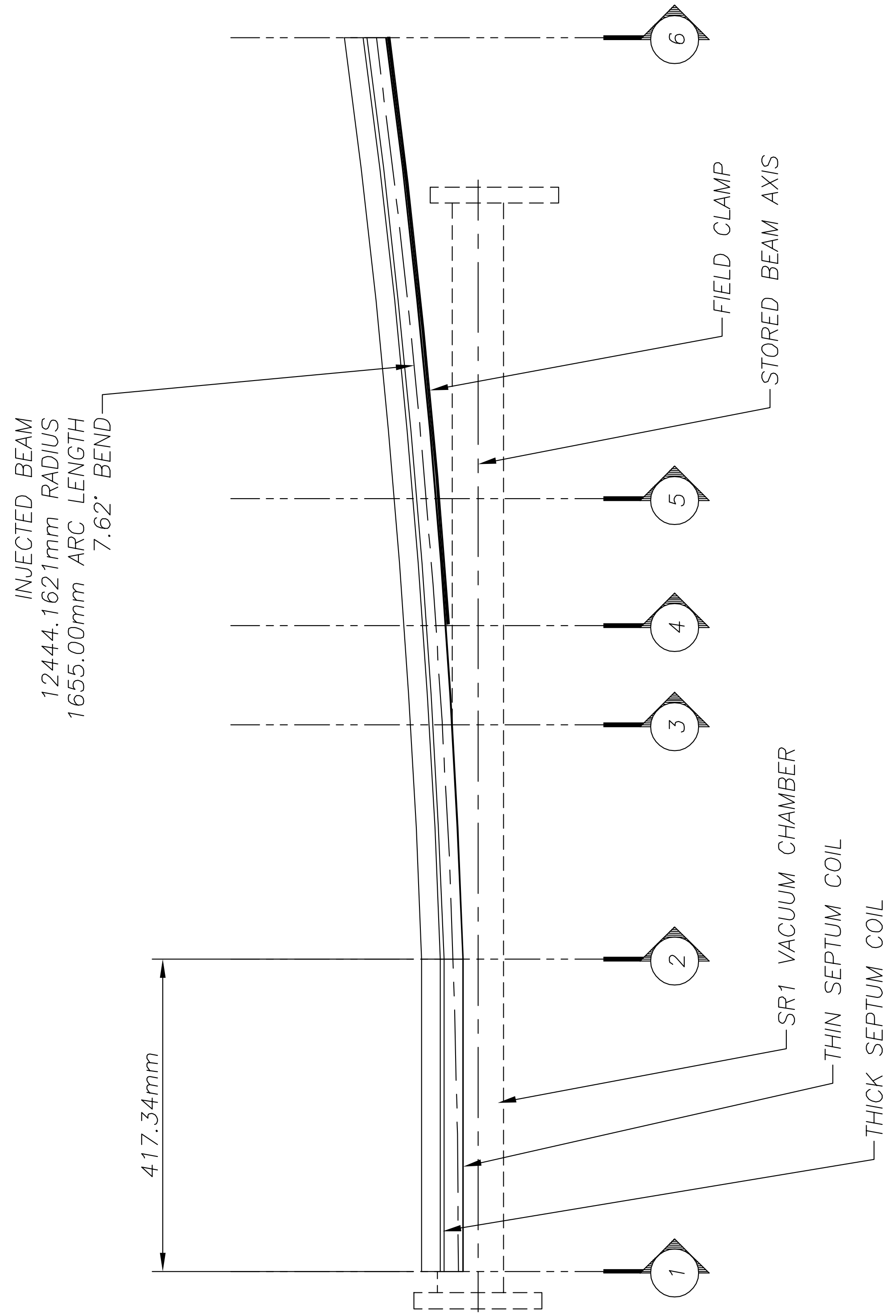

Figure 3.1. Plan View of Thin Septum

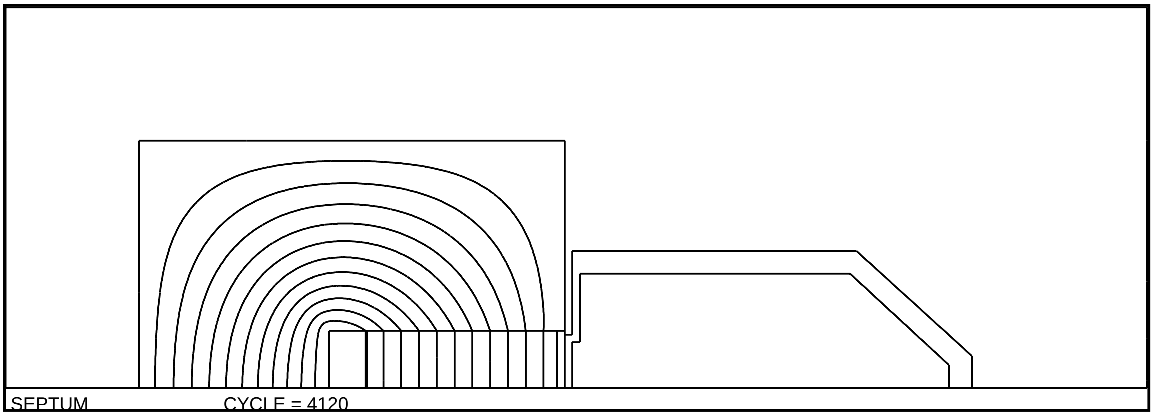

Figure 3.2. Cross-section of Thin Septum Magnet at Positions 1 and 2.

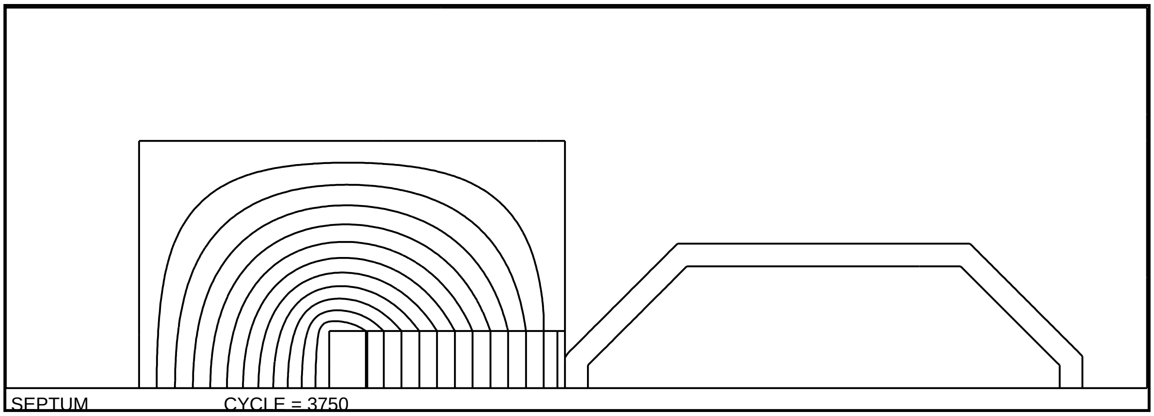

Figure 3.3. Cross-section of Thin Septum Magnet at Position 3.

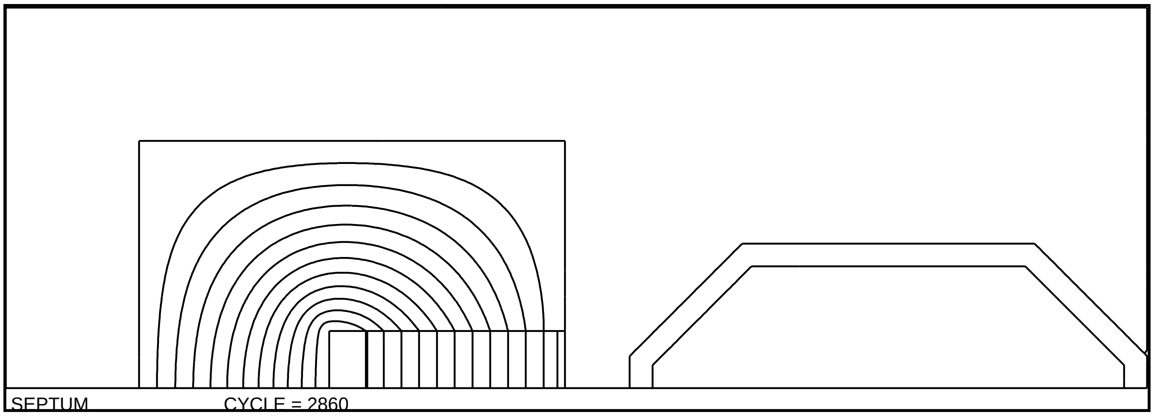

Figure 3.4. Cross-section of Thin Septum Magnet at Position 4.

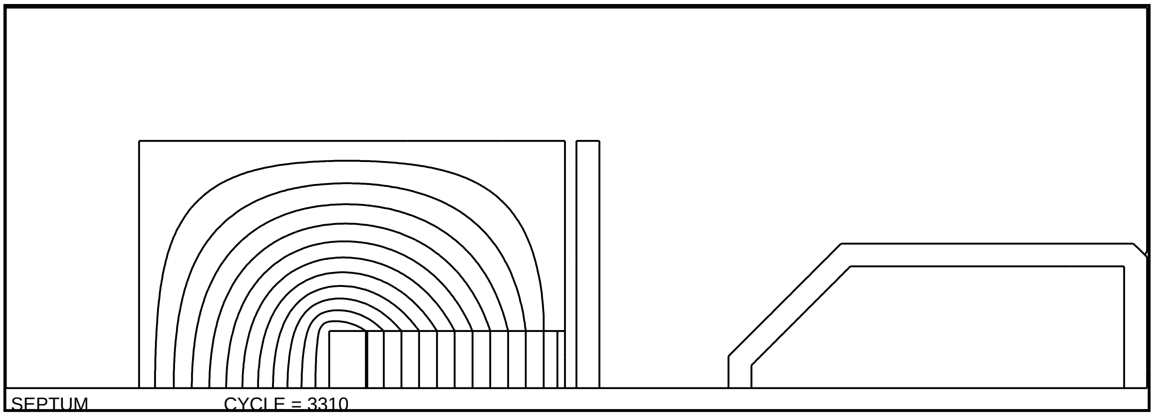

Figure 3.5. Cross-section of Thin Septum Magnet at Position 5.

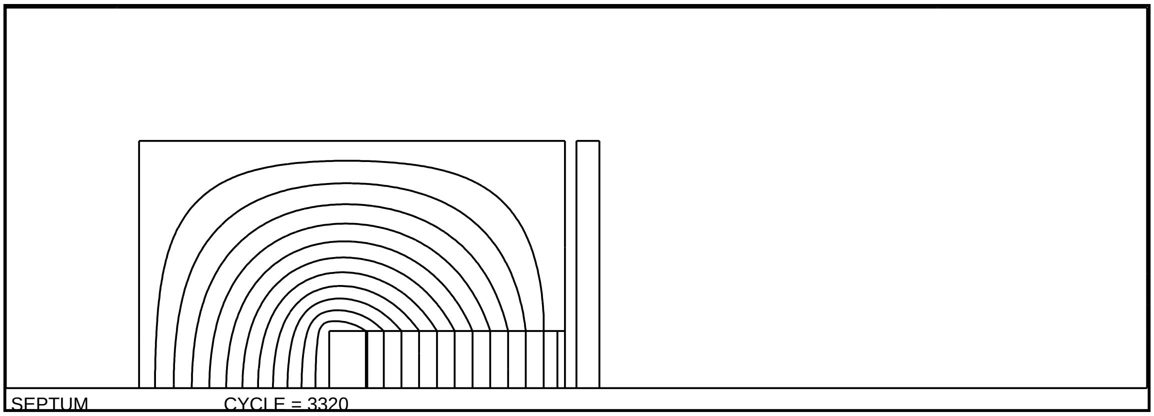

Figure 3.6. Cross-section of Thin Septum Magnet at Position 6.

The Storage Ring (SR1) axis is shielded from the septum field by an iron vacuum chamber. From position 1 to position 2 the thickness of the iron chamber is 1 mm. Not shown is the septum magnet vacuum chamber. Using a vacuum chamber wall thickness of 0.5 mm placed directly against the thin coil would give a total septum thickness of 2.5 mm.

Between positions 1 and 3 the iron SR1 vacuum chamber is not in contact with the magnet yoke. After position 2, the magnet is curving away from the center of the SR1 vacuum chamber until, at position 3, the magnet and vacuum chamber begin to separate. (For ease of construction the magnet in this region could be straight, but at an angle with respect to the downstream straight region.) At position 4, the separation between the magnet and the SR1 vacuum chamber is sufficient to allow the placement of an iron clamp with a thickness of 3 mm. Figure 3.4 shows the cross-section just before the beginning of the clamp while Figure 3.5 shows a cross-section where both the clamp and the SR1 vacuum chamber are shielding the SR1 beam axis. At the upstream end of the magnet, position 6, the SR1 beam axis is shielded by the clamp alone.

The magnet excitations at the various positions are shown in Table 3.1. Also shown is the stray field outside the septum magnet at the positon of the SR1 beam axis. The leakage field at the ends of the septum have not been calculated. The magnetic field is constant through the length of the magnet. The calculated magnet efficiency is greater than 99.5% for all excitations.

Table 3.1. Thin Septum Magnet Excitation.

Position	I	B	B’	B’’	B’’’	E	B_{stray}
	Amperes	T	T/m	T/m^2	T/m^3	GeV	T
1,2	5200	0.43460	-0.006	0.45	21.3	1.622	0.22E-4
1,2	9400	0.78547	-0.015	2.44	147.4	2.932	0.42E-4
1,2	10400	0.86889	-0.015	2.82	1.66.5	3.244	0.48E-4
3	9400	0.78544	-0.017	2.25	116.4	2.932	0.07E-4
4	9400	0.78543	-0.020	1.48	185.2	2.932	0.04E-4
5	9400	0.78546	-0.018	1.98	78.6	2.932	0.01E-4
6	9400	0.78546	-0.018	1.95	73.8	2.932	<0.30E-4

The good field region the thin septum magnet is shown in Figures 3.7 through 3.11 for the defined positions along the magnet. The good field region is adequately uniform through the length of the magnet.

The thin septum magnet parameters are given in Table 3.2.

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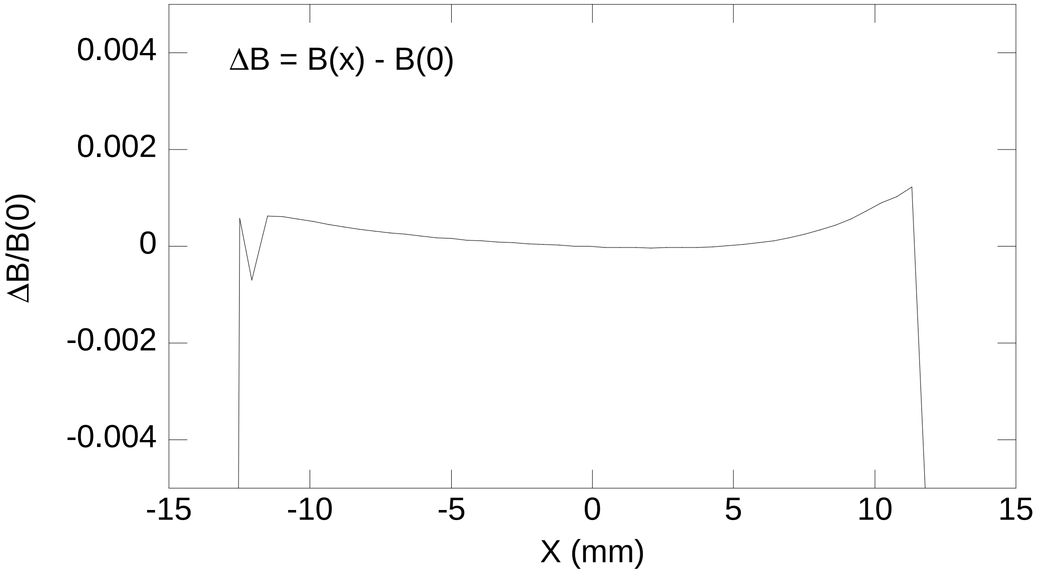

Figure 3.7. Thin Septum Good Field Region at Positions 1 and 2.

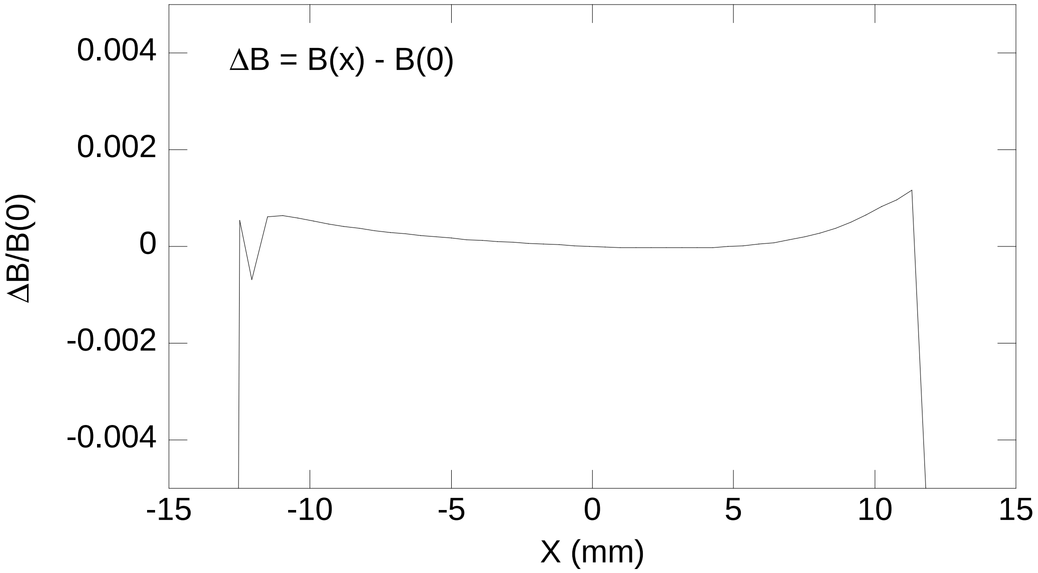

Figure 3.8. Thin Septum Good Field Region at Position 3.

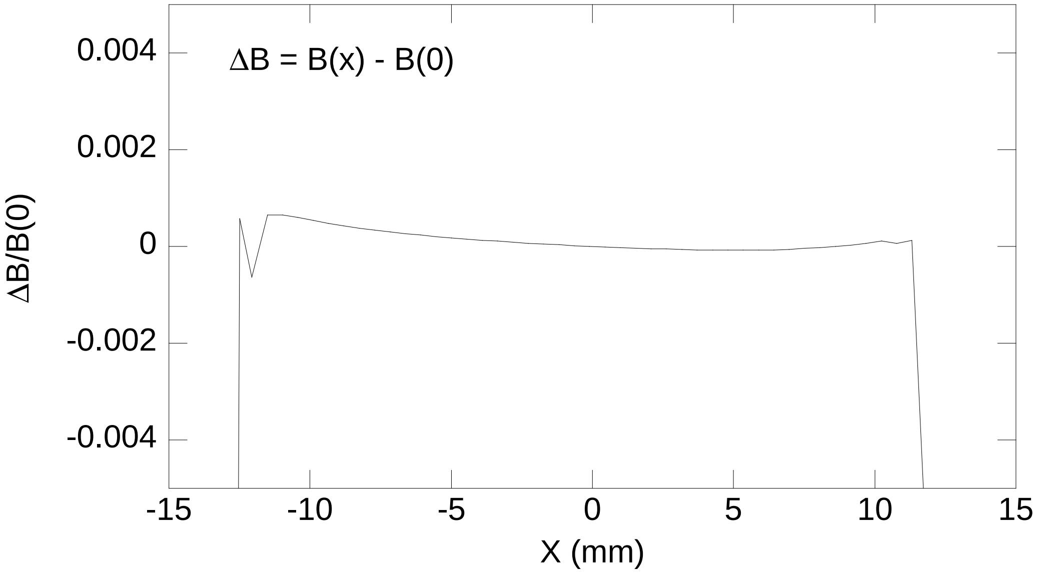

Figure 3.9. Thin Septum Good Field Region at Position 4.

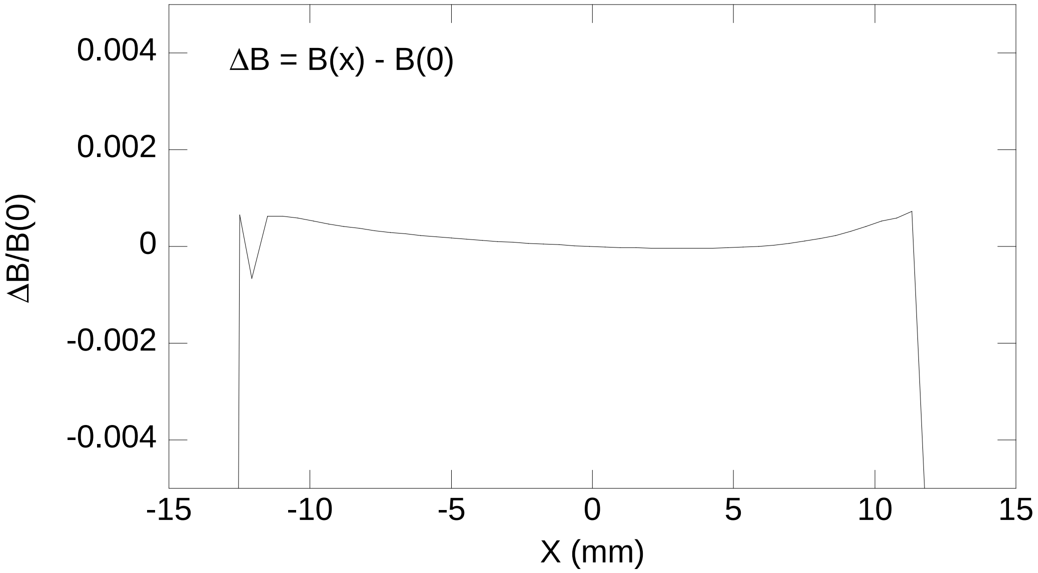

Figure 3.10. Thin Septum Good Field Region at Position 5.

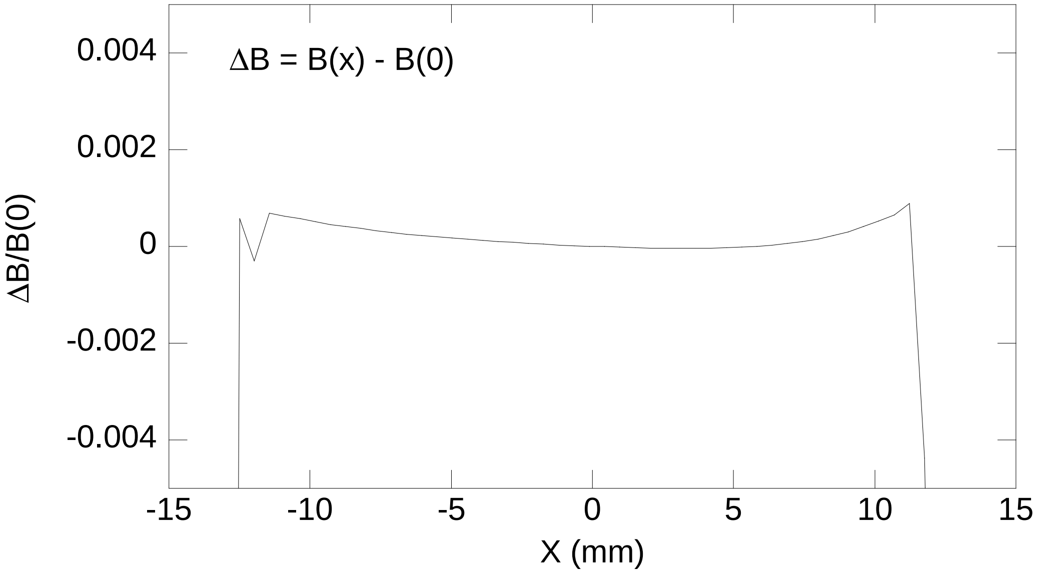

Figure 3.11. Thin Septum Good Field Region at Position 6.

The effects of Eddy currents are considered below. The change in magnetic field inside a circular septum vacuum chamber is given by $\frac{\Delta B}{B} = \mu_0 \sigma \delta r \omega$, where B is the field, μ_0 is the permeability of the vacuum, σ is the conductivity of the vacuum chamber, δ is the thickness of the vacuum chamber, r is the radius of the vacuum chamber and ω is the angular frequency of the power supply wave form. Using:

$\mu_0 = 4\pi \times 10^{-7}$ H/m

$\sigma = 1.35 \times 10^{6}\ \Omega^{-1}\mathrm{m}^{-1}$

$\delta = 0.0005$ m

$r = 0.0075$ m

$\omega = \pi/t_p$ rad/s, where t_p is the pulse length, and

$t_p = 250 \times 10^{-6}$ s

gives $\frac{\Delta B}{B} = -\ 0.08$

Therefore, to account for the losses due to Eddy currents, the currents in Table 3.1 must be multiplied by 1.087. (The effect in an elliptical chamber will be slightly less.)

The inductance of the magnet is given by L = μ_0 lw/g, where l and w are the length and width of the pole and g is the magnet gap. The inductive voltage is given by $V_L = \pi LI/t_p$. The total power is given by $P_{av} = I^2_{rms}Rt_p/t_r$, where $I_{rms} = I/\sqrt{2}$, R is the resistance and t_r is the repetition time.

Table 3.2. Thin Septum Magnet Parameters.

Bend angle		7.62	degrees
Field strength @ 2.9 GeV	B	0.7768	T
Field strength (maximum)	B_{max}	0.8689	T
Magnet arc length	l	1.655	m
Radius of curvature	ρ	12.444	m
Magnet gap	g	15	mm
Pole width	w	25	mm
Maximum current (peak)	I	11300	A
Conductor 1 area		15	mm^2
Conductor 2 area		75	mm^2
Conductor 1 length		1.655	m
Conductor 2 length		1.655	m
Resistance 1 (copper)*	R_1	2.0	mΩ
Resistance 2 (copper)	R_2	0.4	mΩ
Peak voltage drop 1		22.6	V
Peak voltage drop 2		4.5	V
Peak power 1		255	kW
Peak power 2		51	kW
Wave form		half sine	
Half sine duration	t_p	250	µs
Repetition frequency	$1/t_r$	1	Hz
Average power in conductor 1	$P_{av,1}$	32	W
Average power in conductor 2	$P_{av,2}$	6.4	W
Total Power	P_{av}	38.4	W
Inductance	L	3.5	µH
Inductive voltage	V_L	475	V

*resistivity = 1.79E-8 Ω m

4. References

1. R. Mark Silzer, “Injection into the CLS”, Tech. Design Note 2.1.11B, November 19, 1999.

5. Appendices

Appendix I. POISSON (Automesh) input for the thick septum magnet.

```
 THICKSEP AT=7200
$REGNREG=5,DX=.141,DY=.175,XMIN=18.3,XMAX=33.7,YMIN=0.,YMAX=25.,NPOINT=5
$REG KMAX=355,LMAX=143,YREG1=9,MAT=1$
$PO X=-18.3,Y=0. $
$PO X=33.7,Y=0. $
$PO X=33.7,Y=25. $
$PO X=-18.3,Y=25. $
$PO X=-18.3,Y=0. $
$REG MAT=3,CUR=0.,NPOINT=13$
$PO X=-12.8,Y=0. $
$PO X=-6.3,Y=0. $
$PO X=-6.3,Y=11.3 $
$PO X=-3.,Y=11.3 $
$PO X=-3.,Y=.985 $
$PO X=-2.1,Y=.985 $
$PO X=-1.95,Y=1. $
$PO X=1.95,Y=1. $
$PO X=2.1,Y=.985 $
$PO X=3.,Y=.985 $
$PO X=3.,Y=17.3 $
$PO X=-12.8,Y=17.3 $
$PO X=-12.8,Y=0. $
$REG MAT=1,CUR=7200.,NPOINT=5 $
$PO X=-6.15,y=1.25 $
$PO X=-6.15,Y=11. $
$PO X=-3.15,Y=11. $
$PO X=-3.15,Y=1.25 $
$PO X=-6.15,y=1.25 $
$REG MAT=1,CUR=-7200.,NPOINT=5 $
$PO X=3.15,y=1.25 $
$PO X=3.15,Y=11. $
$PO X=6.15,Y=11. $
$PO X=6.15,Y=1.25 $
$PO X=3.15,y=1.25 $
$REG MAT=2,CUR=0.,NPOINT=5 $
```

```
$PO X=7.3,Y=0. $
$PO X=7.3,Y=17.3 $
$PO X=6.3,Y=17.3 $
$PO X=6.3,Y=0. $
$PO X=7.3,Y=0. $
```

Appendix II POISSON (Automesh) input for the thin septum magnet (Position 4).

```
 SEPTUM
$REG NREG=8,DX=.054,DY=.05,XMIN=-6.,XMAX=9.,YMIN=0.,YMAX=5.,NPOINT=5,KMAX=280
$REG LMAX=100,MAT=1$
$PO X=-6.,Y=0. $
$PO X=9.,Y=0. $
$PO X=9.,Y=5. $
$PO X=-6.,Y=5. $
$PO X=-6.,Y=0. $
$REG MAT=2,CUR=00.,NPOINT=8$
$PO X=2.2,Y=0. $
$PO X=2.2,Y=0.421 $
$PO X=3.679,Y=1.9 $
$PO X=5.6,Y=1.9 $
$PO X=7.521,Y=1.9 $
$PO X=9.,Y=.421 $
$PO X=9.,Y=0. $
$PO X=2.2,Y=0. $
$REG MAT=1,CUR=00.,NPOINT=8$
$PO X=2.5,Y=0. $
$PO X=2.5,Y=0.3 $
$PO X=3.8,Y=1.6 $
$PO X=5.6,Y=1.6 $
$PO X=7.4,Y=1.6 $
$PO X=8.7,Y=.3 $
$PO X=8.7,Y=.0 $
$PO X=2.5,Y=0. $
$REG MAT=1,CUR=000.,NPOINT=7$
$PO X=-1.75,Y=0. $
$PO X=-1.75,Y=.75 $
```

```
$PO X=1.15,Y=.75 $
$PO X=1.25,Y=.75 $
$PO X=1.35,Y=.75 $
$PO X=1.35,Y=0. $
$PO X=-1.75,Y=0. $
$REG MAT=2,CUR=000.,NPOINT=9$
$PO X=-1.75,Y=0. $
$PO X=-1.75,Y=.75 $
$PO X=1.15,Y=.75 $
$PO X=1.25,Y=.75 $
$PO X=1.35,Y=.75 $
$PO X=1.35,Y=3.25 $
$PO X=-4.25,Y=3.25 $
$PO X=-4.25,Y=0. $
$PO X=-1.75,Y=0. $
$REG MAT=1,CUR=4700.,NPOINT=5$
$PO X=1.35,Y=0. $
$PO X=1.35,Y=.75 $
$PO X=1.25,Y=.75 $
$PO X=1.25,Y=0. $
$PO X=1.35,Y=0. $
$REG MAT=1,CUR=-4700.,NPOINT=5$
$PO X=-1.75,Y=0. $
$PO X=-1.75,Y=.75 $
$PO X=-1.25,Y=.75 $
$PO X=-1.25,Y=0. $
$PO X=-1.75,Y=0. $
```

Appendix III. B-H curve for AISI 1010 Steel

B (Gauss)	H (Oersted)
5000.	1.13097
10000.	3.39292
11000.	3.99925
12000.	4.83177
13000.	6.02557
13875.	7.64739
14500.	9.49314
15450.	14.9402
15750.	17.6922
16275.	26.1041
16738.	39.1807
17023.	49.881
17275.	60.8677
17583.	76.4199
18088.	107.833
18500.	139.059
19025.	188.32
20500.	414.728
21500.	743.967
22262.	1171.37
22700.	1493.89
23338.	2055.36
24075.	2774.53
26000.	4699.45
30000.	8699.45